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A METEOROLOGICAL STUDY OF THE HIGH SULPHATE AND NITRATE WET DEPOSITION EPISODES IN ONTARIO

Volume 1

FEBRUARY 1992

03/02/92

Ontario Environment Environnement

Environment Canada

Atmospheric Environment Service

ISBN 0-7729-9140-5

A METEOROLOGICAL STUDY OF THE HIGH SULPHATE AND NITRATE WET DEPOSITION EPISODES IN ONTARIO

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Volume 1

PIBS176E01

Report No. ARB-164-91

Environment Canada

Atmospheric Environment Service

FEBRUARY 1992

Ontario

Ministry of the Environment

Executive Summary

This is Volume 1 of the report titled ' A Meteorological Study of the High Sulphate and Nitrate Wet Deposition Episodes in Ontario', number ARB-164-91, published in three volumes.

A co-operative AES (Atmospheric Environment Service) Ontario Region and MOE (Ontario Ministry of the Environment) study was undertaken to investigate the high wet deposition sulphate and nitrate episodes that contributed to the top 25% of annual deposition in 1985-1986 with an objective to determine the meteorological conditions and to analyze the source-receptor relationship of the high deposition episodes. Two CAPMoN (Canadian Air and Precipitation Monitoring Network) stations, viz., Chalk River and Longwoods (AES) and two APIOS (Acidic Precipitation In Ontario Study) stations, Dorset and Longwoods (MOE) were selected in southern and central Ontario. A total of 64 episodes, 31 in 1985 and 33 in 1986, were analyzed to examine the meteorological conditions that yielded different types of precipitation and 72 hour backward trajectories for 1000 mb, 925 mb, 850 mb and 700 mb were computed from a 3D trajectory model.

It was found that SO_2 and NO_x arrived at different levels along the frontal systems and were deposited at the ground by falling precipitation. The sulphate episodes occurred only when either liquid type or liquid type mixed with freezing or frozen precipitation was recorded. The nitrate episodes occurred in all types of precipitation. Lightning appears to be an important NO_x source for some episodes as no anthropogenic sources could be located for these rare cases. Pollution transport, found to have preference for pressure levels (atmospheric altitudes), is most common at high levels (850 mb & 700 mb) from sources in Illinois, Missouri and Chicago area, at high and low (1000 mb & 925 mb) levels from Detroit and at low levels from sources in Ohio, West Virginia and Pennsylvania.

Volume 2 contains Appendix I, and Volume 3 includes Appendix II and Appendix III of the report.

Appendix I of the report describes the 31 (#1.1 to 1.31) high $SO_4^=$ and NO_3^- wet deposition episodes in 1985 at Chalk River, Dorset, Longwoods (AES) and Longwoods (MOE).

Appendix II describes the 33 (#2.1 to 2.33) high $SO_4^=$ and NO_3^- wet deposition episodes in 1986 at Chalk River, Dorset, Longwoods (AES) and Longwoods (MOE).

Appendix III describes the transport index which was developed in an attempt to quantify the source-receptor relationship.

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SUMMARY

A study of the high wet deposition sulphate and nitrate episodes that contributed to the top 25% of annual wet deposition in 1985 and 1986 was undertaken for two CAPMoN and two APIOS stations in southern/central Ontario. A total of 64 separate episodes were selected. Synoptic meteorological conditions that yielded different types of precipitation were examined and 72 hour backward trajectories for 1000 mb, 925 mb, 850 mb and 700 mb were computed. It was found that the episodes occurred due to SO_2 and NO_x arriving at different levels along frontal surfaces and being deposited at the ground by falling precipitation. The high sulphate deposition episodes were associated with either only liquid type or liquid type mixed with freezing or frozen type of precipitation. The high nitrate deposition episodes occurred in all precipitation types. Lightning appears to be an important emission source for some nitrate episodes. There are preferred atmospheric altitudes (levels) for SO_2 and NO_x transport from different sources. The transport is most common at high levels (850 mb and 700 mb) from sources in Illinois, Missouri states and the Chicago area, at high and low levels (1000 mb and 925 mb) from the Detroit area and at low levels from sources in Ohio, West Virginia and Pennsylvania states.

ACKNOWLEDGEMENT

Three co-op students, Mr. Jeff J. Suggett, Mr. Victor A.W. Middleton and Mr. John A. Rampal assisted in this study. The advice and assistance of Mr. Bill Sukloff, AES Measurements and Analysis Research Division (ARQM), for computer analysis of the CAPMoN data and of Mr. Marvin Olson, AES Modelling and Integration Research Division (ARQI), for trajectory computations are acknowledged with thanks. The assistance provided by Dr. A. Tang, MOE, regarding Ontario Ministry of Environment data, is acknowledged with gratitude.

The authors would like to thank Mrs. Billie Beattie, AES Atlantic Region, Scientific Services Division, Halifax, Nova Scotia for critically reviewing the report.

1. INTRODUCTION

A German chemist named Marggraf, in 1749-1750, first discovered nitrate in rainwater. Its importance was realized in agricultural chemistry, and nitrate measurements were made from early techniques in the nineteenth and early twentieth centuries in Europe, North America and other parts of the world. Eriksson (1952a) has tabulated these data. In Canada, the first measurements of nitrogen compounds in precipitation were made during 1908-1924 (Eriksson, 1952a). Angstrom and Hogberg (1952) published data on the nitrogen content of precipitation in Sweden and found that it depended on the characteristics of the air masses.

Sulphur determination in rainwater is relatively recent. It has been carried out mostly in the U.S.A. where an extensive survey of the contribution of atmospheric sulphur to the soil was conducted for agricultural purposes (Eriksson, 1952b).

High levels of acidity in precipitation were first reported in Sweden (Barrett and Brodin, 1955). Later on, the 'acid rain' problem drew attention in North America, and, since the seventies, a large number of studies have been published (e.g.: Cogbill and Likens, 1974; Likens et al., 1979; Likens and Butler, 1981; Jickells et al., 1982; Barrie and Hales, 1984; Barrie et al., 1984; Kurtz et al., 1984; Bhartendu, 1986; Fay et al., 1987; Srivastava,

1987; Ro et al., 1988; Beattie and Whelpdale, 1989; Zeng and Hopke, 1989; Hilst and Chapman, 1990). Recent literature also describes the evidence of acid rain in developing country like India (Khemani et al., 1989; Verma, 1989). Bolin (1971), among others, presented evidence to link the acidity to distant sources.

The ionic content of precipitation is considered to be influenced by the transport of air pollution from anthropogenic sources to downwind distances of hundreds to thousands of kilometres (Barrie and Hales, 1984). An important technique for determining the source regions of the pollution is to compute backward trajectories. This provides useful information on the transport of air pollution, insects, pollen and spores. In AES Ontario Region, a study on blue mold spores (Bhartendu, 1982) proved useful in showing that the tobacco crop in southwestern Ontario in 1979 was most likely destroyed by conidia travelling through the air from the southern U.S.A.

Backward air trajectories have been computed for Hawaii (Miller, 1981), for the Western U.S.A. (Henmi and Bresch, 1985), for APN sites (Barrie et al., 1984), and for Bermuda (Miller and Harris, 1985). The Ontario Ministry of the Environment (Kurtz et al., 1984) has computed 'modified' geostrophic air trajectories for the surface and 850 mb levels for the acidic deposition episode at Dorset, Ontario for the period from August 28 to September 4, 1981. Kurtz et al. (1984) have observed that the pollution source regions

were to the south and southwest of Dorset, Ontario. Barrie et al. (1984) have computed trajectory wind roses and reported that at Chalk River, the high acidity events (pH < 3.8) occurred only for southerly and southwesterly sector trajectories.

An earlier case study of the extreme deposition episodes at the Ontario APN stations (Srivastava, 1987) has been extended to include the top 25% high deposition episodes for two AES CAPMoN (Canadian Air and Precipitation Monitoring Network) stations and two MOE (Ontario Ministry of the Environment) APIOS (Acidic Precipitation in Ontario Study) stations.

The objectives of the study were:

(i) to determine the meteorological conditions of the high deposition episodes; and

(ii) to analyze the source receptor relationships for these episodes.

The following four air quality stations were chosen for this study:

1. Chalk River (AES) - CAPMoN (46°04',77°24')
2. Dorset (MOE) - APIOS (45°13',78°49')
3. Longwoods (AES) - CAPMoN (42°53',81°29')*
4. Longwoods (MOE) - APIOS (42°53',81°29')*

*Actual coordinates are 42°53'02",81°28'52" for Longwoods(AES) and 42°53'02",81°28'50" for Longwoods(MOE).

In order to meet these objectives, $SO_4^=$ and NO_3^- data for 1985-1986 were analyzed for these stations, and the wet deposition episodes which contributed to the top 25% deposition were selected for each of these pollutants. Backward air trajectories were computed using the software developed by Olson et al. (1985). Synoptic surface weather conditions were examined and hourly precipitation records at the nearby weather stations were studied.

This report presents the results of the study of the high wet deposition episodes at Chalk River (AES), Dorset(MOE), Longwoods (AES), and Longwoods (MOE) for 1985-1986. Some data for 1987-1988 were also analyzed to study the source-receptor relationships. Some useful background information is provided and methodology is described.

2. BACKGROUND INFORMATION

2.1 DEPOSITION

The amount of wet deposition per unit area of a particular substance is given by:

$$D_w = C \times P \qquad (1)$$

where D_w = wet deposition amount (mg/m^2)

C = concentration of a substance (mg/l)

P = precipitation amount (mm)

The wet depositions for $SO_4^=$ and NO_3^- were computed in our study for cases when both precipitation and concentration were measured.

A detailed discussion of wet deposition is included in earlier reports (Bhartendu, 1986; Srivastava, 1987).

2.2 UNITS

Normally, the concentration is measured in moles/litre, abbreviated as mole/l. A mole of a substance is the mass numerically equal to its molecular weight.

Therefore:

Concentration (moles/litre) = Concentration(gram/litre)/ molecular wt.

or

C (mole/l) x molecular wt.(g/mole) = C (g/l)

For $SO_4^=$ and NO_3^-

$$D_w\ (mg/m^2) = C\ (mg/l) \times P\ (cm) \times 10 \qquad (2)$$

To convert Deposition to moles/m^2 divide it by the molecular weight; for $SO_4^=$ divide by 96 and for NO_3^- divide by 62.

It should be noted that at the CAPMoN stations, NO_3 concentration is measured directly as nitrate, while at the APIOS stations nitrate is expressed in terms of nitrogen. Therefore, the ratio of concentrations (and wet depositions) at Longwoods (AES) to that at Longwoods (MOE) is 62/14 (= 4.4286)

2.3 AIR TRAJECTORIES

The backward trajectories were computed using the interactive program developed at the AES Air Quality Research Branch by Olson et al. (1985). The trajectory model (Olson et al., 1978) is a 3-dimensional model and combines horizontally analyzed winds with vertical motions computed from the 'Omega equation'. Backward or forward trajectories from surface to 500 mb can be computed and the model operates on a 381 km grid scale. Trajectories were computed on the CRAY computer at the Canadian Meteorological Centre in Montreal and then transferred to Toronto for plotting on the NAS/9060. The procedural steps are described by Olson et al. (1985) and are included in earlier reports (Bhartendu, 1986; Srivastava, 1987).

The air trajectory computations are subject to errors (Djivuc, 1961; Allsopp, 1974) and variations in trajectories computed from different techniques have been reported (Bhartendu, 1982; Haagenson et al., 1987; Kahl et al., 1989).

3. METHODOLOGY

Regional data sets were created for the CAPMoN stations, Longwoods (AES) and Chalk River from the national data archives at the Measurement and Analysis Research Division (ARQM) of Air Quality Research Branch at AES national Headquarters at Downsview. For APIOS stations, namely Dorset and Longwoods (MOE), data sets were provided by the Special Studies and Research Management Unit of the MOE. For each station, the deposition and the percent contribution to the annual deposition of each event for $SO_4^=$ and NO_3^- were computed and the events were ranked in descending order of magnitude for 1985 and 1986 separately, using SAS programming. The statistics on the CAPMoN data for 1985 and 1986 have been published in the CAPMoN Precipitation Chemistry Data Summary reports (Vet et al., 1988a and 1988b). The annual statistics of concentration and deposition for the APIOS stations for 1985 and 1986 have been published by the MOE (Ontario Ministry Of the Environment, 1987; 1988a and 1988b). The Atmospheric Environment Service's (AES) Air Quality and Inter-Environmental Research Branch (ARQD) has

published a number of internal reports describing its different networks, instrumentation, data collection and analysis (Barrie et al., 1980; Barrie and Sirois, 1982; Sirois, 1983; Barrie et al., 1984; Vet et al., 1988a and 1988b). The Ontario Ministry of the Environment has published an overview of its network (1985).

The four air quality stations selected for this study are tabulated in Table 1. For each air quality station, the nearest weather station where hourly precipitation data were available is shown in the table. Distances between the air quality and corresponding weather stations are also shown. A map of the air quality stations is presented in Figure 1. Both the AES and MOE stations at Longwoods were selected to see if any difference existed due to different instrumentation and laboratory analysis of the collected samples. The distance between the two Longwoods stations was approximately 62m. The sample collection period was for 24 hours from 8 a.m. at all the four stations.

The episodes which contributed to the top 25% of the annual wet deposition for $SO_4^=$ and NO_3^- in 1985 and 1986 at each of the above four stations were selected. Synoptic surface weather maps were examined to study the meteorological conditions of each episode. Hourly precipitation records at the nearest weather stations were studied to investigate the relationships of deposition severity with the duration and type of precipitation. The hourly precipitation data at the nearest weather stations are

assumed to be representative of the respective air quality stations. For synoptic frontal storms, this assumption should not cause large errors. The 72 hour backward trajectories of the air parcels for 1000 mb, 925 mb, 850 mb, and 700 mb were computed at these sites. Descriptive narratives for each episode were written. A narrative briefly describes the synoptic condition, type and duration of the precipitation and the air trajectories at the already mentioned four levels for the 24 hour duration of the episode.

Relationships of the deposition severity with precipitation type, duration, and amount were studied. Trajectories were examined to determine the possible transport of pollution from various source regions in eastern North America.

The emission maps for SO_2 and NO_x for the eastern half of North America available at the time of analysis were for 1980. These are presented in Figure 2 and Figure 3 respectively. As indicated in these figures, emissions in kilotonnes per 127 Km Grid are given in four ranges: (i) 50 to 99 ktonne, (ii) 100 to 199 ktonne, (iii) 200 to 399 ktonne, and (iv) 400 and more ktonne. Subsequent to the completion of the analysis, updated maps by ORTECH International were available (private communication, K. Puckett). However, the SO_2 emission scales have been increased from four to eight as shown in Figure 4. Because of this, it is difficult to compare the two maps, but it is clear that the highest emission areas are still

about the same. It should be noted that the SO_4 emission maps for 1985 were also available but the emissions were about an order of magnitude less than the SO_2 emissions. Although no NO_x maps were available for 1985, separate NO and NO_2 maps for more than four scales were available but could not be readily used for the analysis. The NO emission map is exhibited in Figure 5. The NO_2 emissions were generally an order of magnitude less than those for NO.

4. ANALYSIS AND RESULTS

4.1 EPISODES

The episodes which contributed to the top 25% of wet deposition of $SO_4^=$ and NO_3^- at each of the four air quality stations for 1985-1986 were selected. In total 64 episodes were chosen, as shown in Table 2, 31 for 1985 and 33 for 1986. It should be noted that each episode was a 24-hour event and was counted once, even though it may have occurred at more than one station and/or for more than one pollutant at a station. This means that a $SO_4^=/NO_3^-$ event for a particular station will be counted once under the $SO_4^=$ column and once under the NO_3^- column and only once under the total column for the station. For this reason, the sum of the $SO_4^=$ and NO_3^- event totals for each station in Table 2 is not equal to the

total for that station. The same applies for the totals for all stations. The totals for the $SO_4^=$, NO_3^-, and total columns are the sum of the events regardless of station. For example, a particular episode may be included in the numbers for Chalk River, Dorset, and Longwoods, but will only be counted once in the row for all stations in Table 2.

Tables 3.1 and 3.2 tabulate for Chalk River the top 25% sulphate and nitrate wet deposition episodes, respectively, in descending order of deposition amount. The tables list the episode's rank, date, deposition amount (mg/m^2), $SO_4^=$ or NO_3^- concentration (mg/l), individual wet deposition (%), cumulative wet deposition (%), precipitation type, precipitation duration and precipitation amount (mm). The type and duration were determined from the closest weather station as listed in Table 1. Tables 4.1 and 4.2 tabulate these data for Dorset for sulphate and nitrate episodes respectively. Tables 5.1 and 5.2 tabulate the data for sulphate and nitrate episodes respectively for Longwoods (AES). Tables 6.1 and 6.2 tabulate the data for sulphate and nitrate episodes respectively for Longwoods (MOE). It is evident from these tables that the first two or three $SO_4^=$ episodes are also the top two or three NO_3^- episodes. The number 1 ranked event for $SO_4^=$ is ranked either first or second for NO_3^- at all stations, except Dorset, where it is ranked third. Each station has more NO_3^- events than $SO_4^=$ events in both years contributing to the top 25% deposition. Also, the $SO_4^=$ concentration and wet deposition of

individual episodes are generally greater than those for NO_3^-, as shown in Tables 3.1 to 6.2.

In comparing the tables for Longwoods(AES) and Longwoods(MOE) many similarities are observed, but some differences are also found. The number one ranked events for Longwoods (AES) are also the number one ranked events for Longwoods (MOE) except for the NO_3^- episodes in 1986, where the number one ranked MOE event is ranked 2nd for the AES station. The list for the $SO_4^=$ events is similar for the two stations as shown in Tables 5.1 and 6.1. In 1985, 8 events contributed to the top 25% sulphate deposition at both stations, but in 1986, 8 events at Longwoods (AES) and 7 events at Longwoods (MOE) contributed to the top 25% sulphate deposition. For NO_3^- , as stated earlier, the concentrations at Longwoods (AES) are 4.4286 times larger than those at Longwoods (MOE) due to choice of reporting units and, therefore, the deposition values appear larger at AES station in Tables 5.2 as compared to 6.2. For both stations in 1985 and in 1986, ten events contributed to the top 25% nitrate deposition as shown in Tables 5.2 and 6.2. Also, Dorset NO_3^- concentrations should be multiplied by 4.4286 for comparison with the values at Chalk River and Longwoods (AES).

Minor differences between the Longwoods (AES) and Longwoods (MOE) episodes rankings are not unexpected, because of the experimental uncertainties involved in sampling and chemical analysis.

4.2 EPISODES' DESCRIPTION

Narratives were written for each episode to describe the meteorological conditions yielding precipitation and air trajectories at 1000 mb (100.0 kPa), 925 mb (92.5 kPa), 850 mb (85.0 kPa), and 700 mb (70.0 kPa) levels for possible pollution transport from the significant areas exhibited in Figs 2 and 3.

Each narrative gives its ranking in the list of $SO_4^=/NO_3^-$ top 25% wet deposition episodes. Synoptic surface weather conditions for the 24 hour period are described and two surface analysis maps, one at the beginning (mostly at 12Z) and the other at the end (mostly at 12Z) are presented. Table 7 describes the symbols used on the maps. Charts of hourly precipitation (types and duration) are included with each narrative. Precipitation type was recorded as one of, or a combination of, drizzle (L), rain (R), rain showers (RW), thunder showers (TRW), freezing drizzle (ZL), freezing rain (ZR), ice pellets (IP), snow (S), snow grain (SG) and snow showers (SW). Five trajectory maps, for the start day at 12Z, 18Z, and the end day at 00Z, 06Z and 12Z, for the four pressure levels are included with each narrative describing the possible pollutant transport. The 72 hour backward trajectories at 6 hour intervals for 1000 mb, 925 mb, 850 mb, 700 mb levels were computed. For interpretation of the results, 1000 mb and 925 mb levels are called low levels and 850 mb and 700 mb are referred to as high levels in the narratives.

Appendix I (in Volume 2 of the Report) presents the narratives for 31 high deposition episodes in 1985. The episodes are numbered 1.1 to 1.31 and listed by calendar dates. Five episodes are two station events. On March 4-5, 1985 (#1.5), the episode occurred at Longwoods (AES and MOE) and Dorset, on August 18-19, 1985 (#1.16) at Dorset and Chalk River, on August 26-27, 1985 (#1.19) at Longwoods and Chalk River, on September 30-October 1, 1985 (#1.25) at Dorset and Chalk River and on October 12-13, 1985 (#1.27) at Longwoods and Dorset.

Appendix II (in Volume 3 of the Report) presents the narratives for 33 high deposition episodes in 1986. The episodes are numbered 2.1 to 2.33 and listed by calendar dates. Only three episodes are two station events during 1986 and they all occurred at Dorset and Chalk River. These are March 10-11,1986 (#2.7), August 14-15, 1986 (#2.27) and September 4-5, 1986 (#2.30) episodes.

4.3 RELATIONSHIPS OF DEPOSITION SEVERITY WITH METEOROLOGICAL VARIABLES

A review of the narratives revealed that the precipitation for every event was associated with frontal movement over or near the station. Approximately 70% of 1985 events had frontal passage (FROPA) over the station, while in 1986, this figure dropped to

only 58%. The remainder of the events received precipitation from nearby frontal activity that did not include a front crossing over the station.

The precipitation types (see section 4.4) were divided into three categories: (i) liquid including drizzle, rain, rain showers and thundershowers, (ii) freezing with freezing drizzle, freezing rain and ice pellets, and (iii) frozen to include snow and snow showers. These can occur in combinations as shown in Figures 6.1, 6.2, 7.1,7.2,8.1,8.2,9.1 and 9.2. Figures 6.1 and 6.2 show the charts of precipitation types versus episode ranking for 1985 and 1986 of the $SO_4^=$ and NO_3^- deposition respectively at Chalk River. Figures 7.1 and 7.2 present the charts for Dorset, Figures 8.1 and 8.2 for Longwoods (AES) and Figures 9.1 and 9.2 for Longwoods (MOE), respectively.

As evident from Figures 6.1,7.1,8.1 and 9.1, all high sulphate episodes occurred when either liquid precipitation was observed or liquid precipitation with freezing or frozen types of precipitation were recorded. No high episode occurred with only freezing or frozen precipitation. A closer examination of the episodes, discussed in Appendix I and II, showed that if the precipitation type was only snow the episode did not rank high enough to be included in the top 25% sulphate deposition episode list even though the trajectories passed over several highest SO_2 emission regions and the episode was included in the nitrate episode list.

For example, the episode (#1.1, Appendix I, pages I-2 - I-10) on February 18-19, 1985 at Dorset ranked the highest for nitrate but was not included in the list of high sulphate deposition episodes. This occurred, even though the air trajectories passed over the highest SO_2 emission areas of Sudbury and Detroit. Similarly, the episode on February 7-8, 1986 (#2.3, Appendix II, pages II-21 - II-29) at Longwoods (AES) had only snow and was ranked high only for nitrate. As a matter of fact, this episode ranked 57th in the list of sulphate episodes for Longwoods (AES). Also, on February 18-19, 1986 (#2.4, Appendix II, pages II-30 - II-38) at Chalk River, only snow grains, freezing rain and freezing drizzle were observed and the episode was included only in the list of high nitrate depositions. The importance of precipitation type for sulphate deposition becomes clear when we examine the March 10-11, 1986 episode (#2.7, Appendix II, pages II-57 - II-72). This is a two station episode. For Dorset, where rain showers and snow were observed, the episode ranked third highest for sulphate and 2nd highest for nitrate. But for Chalk River, where only ice pellets, freezing rain, freezing drizzle and snow were recorded, the episode ranked high only for the nitrate deposition. The air trajectories indicated possible SO_2 transport from a number of highest emission sources (see pages II-67 - II-72). This is likely due to the better scavenging of sulphate by rain in comparison to that by snow or ice (Hidy and Countess, 1984). The two highest sulphate deposition episodes for all the four stations in 1985 and 1986 occurred with only liquid precipitation.

On the other hand, as shown in Figures 6.2,7.2,8.2, and 9.2, high nitrate episodes occurred with any type or combination of precipitation types.

Precipitation duration was divided into four categories : (i) duration =< 6 hrs, (ii) 6< duration =<12 hrs, (iii) 12< duration =< 18 hrs and (iv) 18< duration =< 24 hrs. The duration by category versus episode ranks is plotted in Figures 10.1, 10.2, 11.1, 11.2, 12.1, 12.2. Figures 10.1 and 10.2 exhibit the plots of precipitation duration versus episodes ranking for 1985 and 1986 for sulphate and nitrate episodes for Chalk River, Figures 11.1 and 11.2 for Longwoods (AES) and Figures 12.1 and 12.2 for Longwoods (MOE) respectively. It should be noted that 24 hour continuous observations for Muskoka were not available and therefore Dorset data were not analyzed. There is no apparent relationship between the precipitation duration and the rankings of the high episodes. However, the highest ranking episode did not fall in the longest duration (18-24 hrs) category at these stations in 1985 and 1986. For the sulphate episodes, one episode (Fig. 11.1) had precipitation in the longest duration category, while for nitrate episodes, five episodes (Figs. 10.2,11.2 and 12.2) had precipitation of longer duration. Every station had at least one such nitrate episode.

Precipitation amounts versus episode rankings are plotted for 1985 and 1986 for $SO_4^=$ and NO_3^- episodes for Chalk River in Figures

13.1 and 13.2, for Longwoods (AES) in Figures 14.1 and 14.2 and for Longwoods (MOE) in Figures 15.1 and 15.2 respectively. Because of the unavailability of 24-hour continuous data from the nearby Muskoka weather station, Dorset data were not analyzed. No relationship between precipitation amount and episode ranking is found as indicated in Figures 13.1 - 15.2. Regression lines plotted (not presented here) between precipitation amount and episode ranking showed mostly, but not always, slight positive slope but with a very large scatter.

It should also be mentioned that there are some cases of high nitrate episodes when the air trajectories do not indicate any possible transport of NO_x from either the highest or high emission source areas. For example, the episode on May 31-June 1, 1986 (#2.15, Appendix II, pages II-141 - II-149) at Chalk River shows the highest ranking nitrate and sulphate event with indication of significant SO_2 transport from Sudbury and Abitibi areas but none of NO_x from any of its source regions. Also, the episode on July 28-29, 1986 (#2.23, Appendix II, pages II-212 - II-220) at Chalk River is a high nitrate event but shows no transport from any high NO_x emission sources. In both cases, lightning was observed and one is led to consider that lightning was likely the source of NO_x.

An episode on August 2-3, 1986 (#2.24 Appendix II, pages II-221 - II-229) at Longwoods also occurred when transport of NO_x from only moderate emission source regions was observed throughout the

entire duration. Lightning was observed. Since no highest or high NO_x emission sources were involved and the episode ranked 5th highest out of ten at both AES and MOE stations and lightning was recorded, it is possible that the lightning may have contributed to its high ranking. However, since transport from moderate anthropogenic sources was present, the importance of lightning could not be established with certainty.

Lightning was observed in about half of the NO_3^- episodes at Chalk River and Longwoods and in about one third of the cases at Dorset. However, continuous observations for 24 hours were not available for the Dorset area, and therefore it is possible that some short duration thunderstorms might have been missed in the records.

The importance of lightning in the production of nitrogen oxides is controversial. Levine et al. (1979) and Levine at al. (1981) report production of nitrate ions due to lightning, while Hill and Rinker (1981) reject this as a significant source. Likens et al. (1987), also, do not find significant contribution from lightning to the nitrate concentration in rain in Australia. Recent work (Liaw et al., 1990) on the global budget of nitrogen fixation by lightning indicates that lightning is the single largest source and that previous estimates (Logan, 1983) were underestimated by about one order of magnitude. Significant NO inside the electrified clouds has also been reported (Chameides et

al., 1987; Davis et al., 1987).

In view of the fact that, for the above mentioned two episodes, no anthropogenic NO_x sources could be found and recent research points out that lightning is more important than previously thought, it is concluded that lightning (and perhaps electrified clouds) was likely the source for high nitrate deposition for these episodes.

4.4 SOURCE-RECEPTOR RELATIONSHIP

In order to determine a source-receptor relationship, the number of trajectories which arrived at the CAPMoN and APIOS stations from each SO_2 and NO_x source (see Figs. 2 and 3) was determined for each pressure levels. The 1000 mb and 925 mb levels were considered as low levels and the 850 mb and 700 mb were regarded as high levels. In a standard atmosphere, the altitudes of the 1000 mb and 925 mb levels are 111 m and 326 m, respectively, and for the 850 mb and 700 mb levels, they are 1.46 Km and 3.01 Km, respectively. The method of determining the number of occurrences was as follows: Each time a trajectory arriving at a station had crossed over an emission square in Figures 2 or 3, or came close enough to indicate a possible transport, it was counted as one occurrence. The number of passes was counted at each pressure level, at high (850 and 700 mb) and low (1000 and 925 mb) levels,

and at any pressure level. An event was only recorded once at a particular level, even if it moved over a source many times during the 24 hour period. It should be noted that the trajectories were plotted only for synoptic hours (ie, 00Z, 06Z, 12Z and 18Z), so information about the trajectory path for the interval between synoptic hours was estimated by consulting the narratives of each episode included in Appendices I and II (see Volumes 2 and 3 of this report). For SO_2 transport, only highest emission sources (greater than 400 kilotonnes per 127 km grid) were examined while both highest and high emission sources (200 to 399 kilotonnes per 127 km grid) were considered for NO_x. This was done because there were only two highest NO_x sources as shown in Figure 3. Also, the two Longwoods stations could not be differentiated for this analysis and therefore they are considered only as one station.

The number of passes have been combined for 1985 and 1986 and summarized in tables for $SO_4^=$ and NO_3^- episodes separately for each station. Tables 8.1 and 8.2 tabulate the 1985-1986 number of occurrences data for $SO_4^=$ and NO_3^- for Chalk River, Tables 9.1 and 9.2 for Dorset and Tables 10.1 and 10.2 for Longwoods, respectively.

The number of occurrences data tabulated in Tables 8.1 to 10.2 were plotted in maps using Harvard Graphics software to give a pictorial representation of a possible source-receptor relationship. Each emission square in the maps was numbered to

correspond to the name of emission source areas in Tables 8.1 - 10.2. Also, inside each square the total number of trajectory passes over the emission area for a particular pollutant was indicated. The number of trajectory passes over a source to the receptor was represented by using arrows. Each arrow was divided into segments of varying widths according to the number of passes at each particular level. For maps representing passes at each pressure level, the arrows were divided into a maximum of four. For the maps showing transport at high and low levels there were a maximum of two divisions and for transport at any level there were no divisions. As shown in the map, shading gets darker as elevation decreases and/or pressure level increases.

Figures 16.1, 16.2 and 16.3 show the number of trajectories from different emission sources arriving at Chalk River in 1985-1986 at each pressure level, at high and low pressure levels and at any pressure level, respectively, for high deposition sulphate episodes. Figures 17.1, 17.2 and 17.3 show the number of trajectories from different emission sources arriving at Chalk River in 1985-1986 at each pressure level, at high and low pressure levels and at any pressure level, respectively, for high deposition nitrate episodes.

Figures 18.1, 18.2 and 18.3 exhibit the number of trajectories, from different emission sources, which arrived at Dorset in 1985-1986 at each pressure level, at high and low

pressure levels and at any pressure level, respectively, for high deposition sulphate episodes. Figures 19.1, 19.2 and 19.3 show the number of trajectories from different emission sources arriving at Dorset in 1985-1986 at each pressure level, at high and low pressure levels and at any pressure level, respectively, for high deposition nitrate episodes.

Figures 20.1, 20.2 and 20.3 show the number of trajectories from different emission source regions arriving at Longwoods in 1985-1986 at each pressure level, at high and low pressure levels and at any pressure level, respectively, for high deposition sulphate episodes. Figures 21.1, 21.2 and 21.3 exhibit the number of trajectories from different emission source regions arriving at Longwoods in 1985-1986 at each pressure level, at high and low pressure levels and at any pressure level, respectively, for high deposition nitrate episodes.

An examination of the above tables and figures, reveals that if we are to consider the possible transport of SO_2 at any pressure level, the Detroit and Chicago areas are the two most frequent source regions for sulphate deposition at Chalk River (Table 8.1 and Fig. 16.3) and Dorset (Table 9.1 and Fig. 18.3). The Detroit area, and the area in Illinois other than the Chicago area are the two most frequent source regions for deposition at Longwoods (Table 10.1 and Fig. 20.3). The Chicago area is the third most frequent source region for sulphate deposition at Longwoods as

indicated in Figure 20.3. However, when we examine the high and low pressure level transport, it is clear that transport from Detroit, Chicago and the other area in Illinois is most frequent at high levels at Chalk River, Dorset and Longwoods. The high level SO_2 transport from the Sudbury area is infrequent for Longwoods (Table 10.1 and Fig. 20.2) but is almost as frequent as that from the non-Chicago area in Illinois for Dorset (Table 9.1 and Fig. 18.2) and Chalk River (Table 8.1 and Fig. 16.2). The low level transport of SO_2 is most frequent from areas in Pennsylvania, closely followed by Detroit, Sudbury and Ohio areas for Chalk River (Table 8.1), the most frequent from Detroit and Ohio areas followed closely by West Virginia area for Dorset (Table 9.1), and the most frequent from Detroit followed by Ohio and West Virginia areas for Longwoods (Table 10.1).

Also, the results are similar for NO_x transport. For NO_3^- deposition at any pressure level for Chalk River (Table 8.2 and Fig. 17.3), Detroit is the most frequent source region, followed by Cleveland and Chicago. The areas in West Virginia, Ohio and Pennsylvania are a close 4th. For NO_3^- deposition at any level for Dorset (Table 9.2 and 19.3), Chicago is the most frequent source, closely followed by Detroit. The Cleveland area and areas in West Virginia, Pennsylvania and Ohio are the third most common source regions. For nitrate deposition at Longwoods (Table 10.2 and Fig. 21.3), Detroit is most frequent, Cleveland the second most and Chicago the third most frequent emission area.

For high level NO_x transport, Chicago, Detroit and the area in Missouri are the three most frequent areas for all three stations (see Tables 8.2, 9.2 and 10.2). For low level transport of NO_x, the Cleveland and Pennsylvania areas are the most frequent and the Ohio area the second most frequent source areas for Chalk River (Table 8.2), Detroit the most and Cleveland the second most frequent source region for Dorset (Table 9.2), and Cleveland the most frequent and Detroit the second most common emission areas for Longwoods (Table 10.2). It should be noted that for low level transport, source regions in West Virginia, Ohio, Detroit and Maryland are also significant for Chalk River; West Virginia, Ohio and Chicago are significant for Dorset; and West Virginia, Ohio, Pennsylvania and Chicago are frequent source areas for deposition at Longwoods.

The above analysis was extended for a further two years (1987 and 1988) and the results were quite similar. Figures 22.1, 22.2 and 22.3 exhibit for 1985-1988 the trajectory occurrences, respectively, for each, high and low, and any pressure levels for $SO_4^=$ high deposition and Figures 23.1,23.2 and 23.3 for NO_3^- high deposition episodes respectively at Chalk River. Tables 11.1 and 11.2 tabulate the actual number of trajectory passes at Chalk River for the total period of 1985-1988 for SO_4^{--} and NO_3^- deposition episodes respectively. Figures 24.1, 24.2, and 24.3 show for 1985-1988 period, the trajectory occurrence for each, high and low and any pressure levels for high sulphate deposition episodes and

Figures 25.1, 25.2 and 25.3 for nitrate high deposition episodes, respectively, for Longwoods. Tables 12.1 and 12.2 tabulate the actual number of trajectory passes at Longwoods for the total period of 1985-1988 for SO_4^{--} and NO_3^- deposition episodes, respectively. The 1987 and 1988 data for Dorset were unavailable at the time of analysis and, therefore, similar maps could not be produced for Dorset. The analysis was also done for separate years to see if there was any variation from year to year. Results (not included in this report) for separate years, 1985, 1986, 1987 and 1988 were similar to the combined results for 1985-1988.

This suggests that the pollution transport from an emission source region to stations in southern and central Ontario is associated with a particular pressure level (atmospheric altitude). The transport from Chicago and other area in Illinois, and Missouri, is more common at high levels, while from areas in Pennsylvania, West Virginia and Ohio at lower levels. Pollution transport from Detroit is equally common at high and low levels.

It should also be noted that we have observed variation in trajectories for levels differing only by 25 mb. For example, the episode on August 24-25, 1985 (#1.18, Appendix I, pages I-172 - I-181) at Longwoods (AES and MOE) showed that even though the trajectory for 850 mb level, one of the standard levels in this report, did not pass over the highest emission area, the 825 mb trajectory did cross over it. This points out the importance of the

pressure level for which the trajectories are computed. For the wet deposition episodes, rain falls from clouds to the ground and would deposit pollutants from the entire column of rain at the ground. The sample collected at the ground contains the total contaminants from this column, although it is mostly agreed that more material is scavenged at cloud level than by falling rain. An experiment to simultaneously collect rain samples from an aircraft and ground could show whether differences exist between samples collected at different heights in the atmosphere.

An unsuccessful attempt to develop an index for quantitative estimation of the transport is described in Appendix III (see Volume 3).

5. CONCLUSION AND DISCUSSION

From this study of 64 episodes in 1985-1986 contributing to the top 25% of sulphate and nitrate wet deposition at Chalk River, Dorset and Longwoods (AES) and Longwoods (MOE) stations, the following conclusions are reached:

(1) The episodes are due to pollutants arriving at different levels along frontal surfaces and being deposited at the surface by falling precipitation at the site. Although all precipitation for these episodes occurred due to frontal activity, actual frontal passage (FROPA) over the site

occurred in 70% of the cases in 1985 and 58% in 1986.

(2) The sulphate episodes had precipitation either of only liquid type or of liquid type mixed with freezing or frozen types. The nitrate episodes had any type of precipitation or a combination of different types.

(3) Lightning is possibly the most significant source for some nitrate episodes.

(4) No linear relationship was found between the deposition severity and precipitation duration or amount for these episodes.

(5) Pollution transport from emission sources to the selected stations in southern and central Ontario was found to have preference for altitudes (pressure levels) in the atmosphere. Pollution transport is most common from Chicago area and other areas in Illinois and Missouri at high levels (850 mb and 700 mb), from Detroit area at high and low levels (925 mb and 1000 mb) and from areas in Ohio, West Virginia and Pennsylvania at low levels. Transport from New York, New Jersey and Maryland areas is infrequent.

(6) Significant transport of SO_2 from Sudbury to Chalk River and Dorset occurs more frequently at high levels than at low levels. Such transport to Longwoods is rare.

It is clear that there are preferred altitudes for SO_2 and NO_x transport from different sources. The sources from which high level transport is more common are mostly located in the west to southwest direction from the stations. On the other hand, low level transport is more common from sources situated south west to south east from the stations. This could be due to more frequent westerly winds at high altitudes.

Notwithstanding the errors in air trajectory computations, the air trajectory is a very important indicator of the source-receptor transport. The trajectory results presented in this report should not be interpreted as a proof but as an indicator of the transport. The consistency of the directions of trajectories during an episode provides a good indicator of the paths traversed by the air parcels.

6. REFERENCES

Allsopp, T.R., 1974: Investigation into a Three-Dimensional Air Parcel Trajectory Model with Applications to Canada. M.Sc. Thesis, University of Toronto, 108 pp.

Angstrom, A. and Hogberg, L., 1952: On the Content of Nitrogen in Atmospheric Precipitation in Sweden II, Tellus, **4**, 271-279.

Barrett, E. and Brodin, G., 1955: The Acidity of Scandinavian Precipitation, Tellus, **7**, 251-257.

Barrie, L.A., Anlauf, K., Wiebe, H.A. and Fellin, P., 1984: Acidic Pollutants in Air and Precipitation at Selected Rural Locations in Canada, published in Acid Precipitation Series, **4**, Edited by J.I. Teasley, Butterworth Publishers, Toronto, 15-35.

Barrie, L.A. and Hales, J.M., 1984: The Spatial Distributions of Precipitation Acidity and Major Ion Wet Deposition in North America during 1980. Tellus, **36B**, 333-355.

Barrie, L.A. and Sirois, A., 1982: An Analysis and Assessment of Precipitation Chemistry Measurements Made by CANSAP (The Canadian Network for Sampling Precipitation): 1977-1980, Internal Report: AQRB-82-003-T, Atmospheric Dispersion Division, Air Quality and Inter-Environmental Research Branch, AES, Downsview, Ontario, Canada M3H 5T4, 163 pp.

Barrie, L.A., Wiebe, H.A. and Anlauf, K., 1984: Results of the Canadian Air and Precipitation Monitoring Network APN: 1982, Internal Report: ARQB-84-005-T, Air Quality Monitoring and Assessment Division, Air Quality and Inter-Environmental Research Branch, AES, Downsview, Ontario Canada, M3H 5T4, 10 pp. + 9 Appendices.

Barrie, L.A., Wiebe, H.A., Fellin, P. and Anlauf, K., 1980: APN The Canadian Air and Precipitation Monitoring Network: A Description and Results for November 1978 to June 1979. Internal Report; AQRB-80-002-T, Atmospheric Dispersion Division, Air Quality and Inter-Environmental Research Branch, AES, Downsview, Ontario, Canada M3H 5T4, 27 pp & 5 Appendices.

Beattie, B.L and Whelpdale, D.M., 1989: Meteorological Characteristics of Large acidic Deposition Events at Kejimkujik, Nova Scotia, Water, Air and Soil Pollution, **46**, 45-59.

Bhartendu, S., 1982: Meteorological Conditions of the Transport and Outbreak of Blue Mold Spores of Tobacco in Southern Ontario Region. Internal Report SSD-82-5, AES Ontario Region, 32 pp.

Bhartendu, S., 1986: A Case Study of the Extreme Deposition Episode at Chalk River, Ontario in 1982. Internal Report SSD-86-1, AES Ontario Region, 66pp.

Bolin, B., 1971: Air Pollution Across National Boundaries: The Impact on the Environment of Sulphur in Air and Precipitation. Report of Swedish Precipitation Committee for UN Conferences on Human Environment, Kungl. Boklrycheriet, P.A. Norstedt et Soner, Stockholm, 96 pp.

Chameides, W.L., Davis, D.D., Bradshaw, J., Rodgers, M., Sandholm, S., and Bai, D.B., 1987: An Estimate of the NO_x Production Rate in Electrified Clouds based on NO observations from the GTE/CITE 1 Fall 1983 Field Operation. Journal of Geophysical Research, **92**, Number D2, 2153-2156.

Cogbill, C.V. and Likens, G.E., 1974: Acid Precipitation in the Northeastern United States. Water Resources Research, **10**, 1133-1139.

Davis, D.D., Bradshaw, J.D., Rodgers, M.O., Sandholm, S.T. and Keshing, S., 1987: Free Tropospheric and Boundary Layer Measurements of NO over the Central and Eastern North Pacific Ocean. Journal of Geophysical Research, **92**, Number D2, 2049-2070.

Djivuc, D., 1961: On the Accuracy of Air Trajectory Computations. Journal of Meteorology, **18**, 597-605.

Eriksson, E., 1952a: Composition of Atmospheric Precipitation (1). Nitrogen Compounds. Tellus. **4**, 215-232.

Eriksson, E., 1952b: Composition of Atmospheric Precipitation (2). Sulphur, Chloride, Iodine Compounds, Bibliography. Tellus, **4**, 280-283.

Fay, J.A., Golomb, D. and Kumar, S., 1987: Anthropogenic Nitrogen Oxide Transport and Deposition in Eastern North America, Atmospheric Environment, **21**, No. 1, 61-68.

Haagenson, P.L., Kuo, Y.H., Skumanich, M. and Seaman, N., 1987: Tracer Verification of Trajectory Models. Journal of Climate and Applied Meteorology, **26**, 410-427.

Henmi, T. and Bresch, J.F., 1985: Meteorological Case Studies of Regional High Sulphur Episodes in the Western United States, Atmospheric Environment, **19**, 1783-1796.

Hidy, G.M. and Countess, R., 1984: Combined Analysis of Air Quality and Precipitation Chemistry Data, Chapter 3, in Deposition Both Wet and Dry, edited by B.B. Hicks, Acid Precipitation Series - **4**, J.I. Teasley, Series Editor, Butterworth Publishers, Toronto.

Hill, R.D. and Rinker, R.G., 1981: Production of Nitrate Ions and Other Trace Species by Lightning, Journal of Geophysical Research, **86**, Number C4, 3203-3209.

Hilst, G.R. and Chapman, E.G., 1990: Source-Receptor Relationship for Wet SO_4^{--} and NO_3^- Production, Atmospheric Environment, **24A**, 1889-1901.

Jickells, T., Knap, A., Church, T., Galloway, J. and Miller, J. 1982: Acid Rain on Bermuda, Nature, **297**, Number 5861, 55-57.

Kahl, J.D., Harris, J.M., Herbert, G.A. and Olson, M.P., 1989: Intercomparison of Three Long-range Trajectory Models Applied to Arctic Haze. Tellus, **41B**, 524-536.

Khemani, L.T., Momin, G.A., Rao, P.S.P., Safai, P.D., Singh, G. and Kapoor, R.K., 1989: Spread of Acid Rain over India, Atmospheric Environment, **23**, 747-762.

Kurtz, J., Tang, A.J.S., Kirk, R.W. and Chan, W.H. 1984: Analysis of an Acidic Deposition Episode at Dorset, Ontario, Atmospheric Environment, **18**, 377-394.

Levine, J.S., Hughes, R.E., Chameides, W.L., Howell, W.E., 1979: N_2O and CO Production by Electrical Discharge: Atmospheric Implications, Geophysical Research Letters, **6**, 557-559.

Levine, J.S., Brooke, R.R., Shawa, E.F., Chameides, W.L., 1981: Aircraft Measurements of N_2O Enhancement in Thunderstorm Lightning, EOS, **62**, Number 7, p. 290 (Abstract).

Liaw, Y.P., Sisterson, D.L. and Miller,N.L., 1990: Comparison of Field, Laboratory, and Theoretical Estimates of Global Nitrogen Fixation by Lightning, Journal of Geophysical Research, **95**, 22489-22494.

Likens, G.E., Wright, R.F., Galloway, J.N. and Butler, T.J., 1979: Acid Rain, Scientific American, **241**, 43-51.

Likens, G.E. and Butler, T.J., 1981: Recent Acidification of Precipitation in North America, Atmospheric Environment, **15**, 1103-1109.

Likens, G.E., Keene, W.C., Miller, J.M. and Galloway, J.N., 1987: Chemistry of Precipitation from a Remote Terrestrial Site in Australia, Journal of Geophysical Research, **92**, 13299-13314.

Logan, J.A., 1983: Nitrogen Oxides in the Troposphere: Global and Regional Budgets, Journal of Geophysical Research, **88**, 10785-10807.

Miller, J.M., 1981: A five year climatology of Back Trajectories from the Mauna Loa Observatory, Hawaii, Atmospheric Environment, **15**, 1553-1558.

Miller, J.M. and Harris, J.M., 1985: The Flow Climatology to Bermuda and Its Implications for Long-Range Transport, Atmospheric Environment, **19**, 409-414.

Olson, M.P., Oikawa, K.K. and MacAfee, A.W., 1978: A Trajectory Model Applied to the Long-Range Transport of Air Pollutants - A Technical Description and Some Model Intercomparison. AES, Internal Report LRTAP 78-4.

Olson, M.P., Panigas, A. and Oikawa, K.K., 1985: A User Guide to the Interactive Trajectory Computation and Plotting System (ITCAPS), Internal Report AQRB-85-006-T, Atmospheric Dispersion Division, Air Quality and Inter-Environmental Research Branch, AES, Downsview, Ontario, Canada 22pp, and 17 pp of illustrative examples.

Ontario Ministry of the Environment, 1985: Acidic Precipitation In Ontario Study, An Overview: The Event Wet Dry Deposition Network (First Revised Edition), Report Number ARB-142-85-AQM.

Ontario Ministry of the Environment, 1987: Acid Precipitation In Ontario Study, Annual Statistics of Concentration and Deposition - Cumulative Precipitation Monitoring Network, 1985, ARB-006-87-AQM, APIOS-002-87, 168 pp.

Ontario Ministry of the Environment, 1988a: Acid Precipitation In Ontario Study, Annual Statistics of Concentration and Deposition - Cumulative Precipitation Monitoring Network, 1986, ARB-039-88, APIOS-007-88, ISSN 0824-880X, ISSN 0830-162X, 172 pp.

Ontario Ministry of the Environment, 1988b: Acid Precipitation In Ontario Study, Annual Statistics of Concentration and Deposition Daily Precipitation and Air Monitoring Network, 1986, ARB-038-88, APIOS-006-88, ISSN 0824-880X, ISSN 0830-1646, 46 pp.

Ro, C.U., Tang, A.J.S., Chan, W.H., Kirk, R.W., Reid, N.W. and Lusis, M.A., 1988: Wet and Dry Deposition of Sulphur and Nitrogen Compounds in Ontario, Atmospheric Environment, **22**, 2763-2772.

Srivastava, B., 1987: A Study of the Extreme Deposition Episodes During 1982 at the APN Stations in Ontario, Internal Report SSD-87-2, Ontario Region, Atmospheric Environment Service, 146 pp.

Verma, G.S., 1989: Background Trends of pH of Precipitation over India, Atmospheric Environment, **23**, 747-751.

Vet, R.J., Sukloff, W.B., Still, M.E., Martin, J.B., Kobelka, W.F., and Gaudenzi, A.J., 1988a: Canadian Air and Precipitation Monitoring Network (CAPMoN) Precipitation Chemistry Data Summary 1985, Report AQRB-88-01, Air Quality Monitoring and Assessment Division, Air Quality and Inter-Environmental Research Branch, AES, 482 pp.

Vet, R.J., Sukloff, W.B., Still, M.E., Martin, J.B., Kobelka, W.F., and Gaudenzi, A.J., 1988b: Canadian Air and Precipitation Monitoring Network (CAPMoN) Precipitation Chemistry Data Summary 1986, Report AQRB-88-02, Air Quality Monitoring and Assessment Division, Air Quality and Inter-Environmental Research Branch, AES, 468 pp.

Zeng, Y. and Hopke, P.K, 1989: A Study of the Sources of Acid Precipitation in Ontario, Canada, Atmospheric Environment, **23**, 1499-1509.

Table 1 - AIR QUALITY AND WEATHER STATIONS

Air Quality	Weather	Distance (km)
Chalk River (AES) - CAPMoN (46°04',77°24',122m)	Petawawa Airport (45°57',77°19',130m)	14.5
Dorset (MOE) - APIOS (45°13',78°49',320m)	Muskoka Airport (44°58',79°18',280m)	47.0
Longwoods (AES) - CAPMoN (42°53',81°29',278m)	London Airport (43°02',81°09',278m)	31.8
Longwoods (MOE) - APIOS (42°53',81°29',278m)	London Airport (43°02',81°09',278m)	31.8

Table 2 - EPISODE TOTALS

Station	$SO_4^=$	NO_3^-	Total*
	1985		
Chalk River (AES)	5	7	8
Dorset (MOE)	8	12	14
Longwoods (AES&MOE)	9	13	14
All Stations	17	29	31
	1986		
Chalk River (AES)	6	8	11
Dorset (MOE)	7	10	12
Longwoods (AES&MOE)	8	11	13
All Stations	19	27	33

* See text (page 10) for explanation.

Table 3.1 - CHALK RIVER (AES)

$SO_4^=$ Wet Deposition Episodes

(Units: Dep amt-mg/m^2, Concen-mg/l, Precip: dur-hr, amt-mm, type see text [page 13])

1985

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Aug. 18-19	116.82	5.90	6.6	6.6	TRW	10	19.8
2	July 5-6	112.82	5.19	6.3	12.9	RW,TRW	4	21.7
3	Apr. 13-14	83.30	8.01	4.7	17.6	IP,ZR,R,RW	7	10.4
4	Aug. 26-27	68.78	2.89	3.9	21.4	RW,TRW	9	23.8
5	Sep. 30-Oct. 1	65.07	3.92	3.7	25.1	R,RW,L	15	16.6

1986

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	May 31-June 1	127.14	5.48	7.5	7.5	RW,TRW	4	23.2
2	Sep. 4-5	78.30	2.70	4.6	12.2	RW,TRW	4	29.0
3	Aug. 14-15	74.25	11.25	4.4	16.5	RW,TRW	5	6.6
4	May 5-6	73.47	4.65	4.4	20.9	RW,L	11	15.8
5	Aug. 10-11	61.79	8.13	3.7	24.6	R,RW	3	7.6
6	Aug. 23-24	61.20	8.27	3.6	28.2	RW,L	11	7.4

Table 3.2 - CHALK RIVER (AES)

NO_3^- Wet Deposition Episodes

(Units: Dep amt-mg/m^2, concen-mg/l, precip: dur-hr, amt-mm, type see text [p 13])

1985

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Apr. 13-14	69.98	6.73	4.6	9.2*	ZR,IP,R,RW	7	10.4
2	Aug. 18-19	48.21	2.44	3.2	12.3	RW,TRW	10	19.8
3	July 5-6	44.19	2.04	2.9	15.2	RW,TRW	4	21.7
4	June 23-24	41.43	1.73	2.7	17.9	RW,TRW	4	24.0
5	Sep. 30-Oct. 1	39.68	2.39	2.6	20.5	R,RW,L	15	16.6
6	Apr. 14-15	39.42	3.72	2.6	23.0	R,RW	9	10.6
7	Sep. 26-27	36.88	1.55	2.5	25.6	R,RW,L	16	23.8

* The cumulative deposition (%) includes Mar 11-12 episode which was excluded from the analysis due to poor ion balance.

1986

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	May 31-June 1	70.86	3.05	5.2	5.2	RW,TRW	4	23.2
2	Jan. 19-20	60.72	4.78	4.5	9.7	R,RW,L	18	12.7
3	Mar. 10-11	44.89	2.88	3.3	13.0	S,RW	8	15.6
4	Aug. 14-15	37.40	5.67	2.8	15.8	RW,TRW	5	6.6
5	July 28-29	34.86	1.37	2.6	18.4	RW,TRW	8	25.4
6	May 5-6	34.27	2.17	2.5	20.9	RW,L	11	15.8
7	May 17-18	32.43	4.19	2.4	23.2	RW,TRW	2	6.6
8	Feb. 18-19	29.31	14.65	2.2	25.4	SG,ZR,ZL	23	2.0

Table 4.1 - DORSET (MOE)

$SO_4^=$ Wet Deposition Episodes

(Units: Dep amt-mg/m^2, Concen-mg/l, Precip: dur-hr, amt-mm, type see text [page 13])

1985

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Aug. 18-19	99.45	5.85	4.3	4.3	RW,TRW	7	17.0
2	Oct. 12-13	76.56	2.20	3.3	7.6	R,RW,L	6	34.8
3	Sep. 3-4	75.60	2.00	3.2	10.8	RW	4	37.8
4	May 5-6	69.54	2.85	3.0	13.8	R,RW,L	15	24.4
5	Aug. 29-30	69.36	2.40	3.0	16.8	RW,L	8	28.9
6	Apr. 5-6	67.62	3.45	2.9	19.7	RW	9	19.6
7	Sep. 30-Oct. 1	64.17	4.65	2.8	22.4	R,RW,L	4	13.8
8	Aug. 6-7	63.36	4.95	2.7	25.1	RW	4	12.8

1986

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Sep. 4-5	128.00	4.00	6.0	6.0	RW,TRW	2	32.0
2	Aug. 14-15	114.66	6.30	5.4	11.4	RW,TRW	4	18.2
3	Mar. 10-11	73.92	3.85	3.5	14.9	S,RW	8	19.2
4	Aug. 26-27	68.67	6.30	3.2	18.1	R,RW	4	10.9
5	Aug. 8-9	65.83	1.45	3.1	21.2	RW,TRW	3	45.4
6	Jan. 25-26	65.19	5.30	3.1	24.3	S,SW,SG,R,L	15	12.3
7	June 22-23	58.96	6.70	2.8	27.1	RW,TRW	7	8.8

Table 4.2 - DORSET (MOE)

NO_3^- Wet Deposition Episodes

(Units: Dep amt-mg/m^2, Concen-mg/l, Precip: dur-hr, amt-mm, type see text [page13])

1985

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Feb. 18-19	13.73	1.04	2.7	2.7	S,SW	6	13.2
2	Sep. 30-Oct. 1	12.14	0.88	2.4	5.1	R,RW,L	4	13.8
3	Aug. 18-19	11.90	0.70	2.3	7.4	R,RW,L	7	17.0
4	Apr. 5-6	11.76	0.60	2.3	9.7	RW	9	19.6
5	May 5-6	11.71	0.48	2.2	12.0	R,RW,L	15	24.4
6	Nov. 18-19	11.14	0.58	2.1	14.2	R,RW	5	19.2
7	Mar. 4-5	10.56	0.28	1.9	16.3	S,IP	16	3.7
8	May 15-16	9.82	1.61	1.9	18.2	RW	3	6.1
9	Sep. 3-4	9.45	0.25	1.8	20.0	RW	4	37.8
10	Oct. 4-5	9.07	0.81	1.8	21.8	RW	1	11.2
11	Feb. 21-22	9.05	0.87	1.7	23.6	R,RW	3	10.4
12	Aug. 6-7	8.45	0.66	1.6	25.3	RW	4	12.8

1986

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Jan. 25-26	17.34	1.41	4.1	4.1	S,SW,SG,R,L	15	12.3
2	Mar. 10-11	14.02	0.73	3.3	7.3	S,RW	8	19.2
3	Sep. 4-5	13.12	0.41	3.1	10.4	RW,TRW	2	32.0
4	July 19-20	11.02	0.29	2.6	13.0	------	-	38.0
5	Aug. 14-15	10.37	0.57	2.4	15.4	RW,TRW	4	18.2
6	Mar. 18-19	9.39	0.77	2.2	17.7	R	12	12.2
7	Aug. 26-27	9.27	0.85	2.2	19.8	R,RW	4	10.9
8	Mar. 6-7	7.74	0.86	1.8	21.6	S	15	9.0
9	June 16-17	6.15	0.25	1.4	24.5	RW,TRW	3	24.6
10	Oct. 14-15	6.14	0.22	1.4	26.0	IPW,RW,L	10	27.9

Table 5.1 - LONGWOODS (AES)

$SO_4^=$ Wet Deposition Episodes

(Units: Dep amt-mg/m^2, Concen-mg/l, Precip: dur-hr, amt-mm, type see text [page 13])

1985

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Sep. 7-8	164.08	2.93	5.2	5.2	RW,TRW	4	56.0
2	Aug. 23-24	162.71	8.94	5.2	10.4	R,RW	7	18.2
3	Mar. 4-5	94.67	2.94	3.0	13.5	S,SW,IP,ZR,R	17	32.2
4	Oct. 18-19	89.01	1.87	2.8	16.3	R,RW	17	47.6
5	Oct. 12-13	82.60	3.50	2.6	19.0	R,RW,L	12	23.6
6	Aug. 26-27	82.50	3.30	2.6	21.6	RW,TRW,L	3	25.0
7	Feb. 23-24	70.20	2.34	2.2	23.8	R,L	22	30.0
8	Aug. 14-15	65.67	2.88	2.1	25.9	RW,TRW	4	22.8

1986

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Sep. 10-11	209.44	8.80	7.0	7.0	R,RW,TRW	15	23.8
2	July 25-26	158.46	4.17	5.3	12.4	RW,TRW	7	38.0
3	July 12-13	85.20	1.79	2.9	15.2	RW,L	8	47.6
4	July 11-12	79.38	2.94	2.7	17.8	R,RW	15	27.0
5	Apr. 28-29	67.86	11.31	2.3	20.2	RW,TRW	4	6.0
6	Sep. 15-16	63.83	3.16	2.1	22.3	R,RW	7	20.2
7	June 11-12	61.75	2.47	2.1	24.3	R,RW,TRW	12	25.0
8	Apr. 20-21	61.50	2.46	2.1	26.4	R,RW,L	15	25.0

Table 5.2 - LONGWOODS (AES)

NO_3^- Wet Deposition Episodes

(Units: Dep amt-mg/m^2, Concen-mg/l, Precip: dur-hr, amt-mm, type see text [page 13])

1985

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Aug. 23-24	133.74	7.35	5.3	5.3	R,RW	7	18.2
2	Sep. 7-8	106.60	1.90	4.2	9.6	RW,TRW	4	56.0
3	Oct. 18-19	86.39	1.82	3.4	13.0	R,RW	17	47.6
4	Nov. 9-10	60.87	2.44	2.4	15.4	R,RW,L	21	25.0
5	Feb. 23-24	46.48	1.55	1.9	17.3	R,L	22	30.0
6	Mar. 4-5	44.19	1.37	1.8	19.0	S,SW,IP,ZR,R	17	32.2
7	Aug. 24-25	42.85	1.77	1.7	20.7	R,RW	13	24.2
8	May 26-27	42.44	6.24	1.7	22.5	R,RW,TRW	12	6.8
9	Aug. 26-27	42.06	1.68	1.7	24.1	RW,TRW,L	3	25.0
10	Aug. 14-15	41.38	1.82	1.6	25.7	RW,TRW	4	22.8

1986

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Apr. 15-16	70.78	5.45	3.1	3.1	R,RW,L	6	13.0
2	Sep. 10-11	70.59	2.97	3.1	6.1	R,RW,TRW	15	23.8
3	July 25-26	62.24	1.64	2.7	8.8	RW,TRW	7	38.0
4	Feb. 7-8	60.75	4.16	2.6	11.4	S	24	14.6
5	Aug. 2-3	59.50	2.83	2.6	14.1	R,RW,TRW	3	21.0
6	Apr. 28-29	58.70	9.78	2.5	16.6	RW,TRW	4	6.0
7	Mar. 5-6	58.54	3.85	2.5	19.1	S	12	15.2
8	July 12-13	50.57	1.06	2.2	21.3	RW,L	8	47.6
9	Apr. 7-8	49.40	5.49	2.1	23.5	RW,TRW,L	3	9.0
10	Apr. 20-21	47.59	1.90	2.1	25.5	R,RW,L	15	25.0

Table 6.1 - LONGWOODS (MOE)

$SO_4^=$ Wet Deposition Episodes

(Units: Dep amt-mg/m^2, Concen-mg/l, Precip: dur-hr, amt-mm, type see text [page 13])

1985

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Sep. 7-8	177.60	3.00	5.9	5.9	RW,TRW	4	59.2
2	Aug. 23-24	160.16	8.80	5.3	11.3	R,RW	7	18.2
3	Oct. 18-19	102.34	2.15	3.4	14.7	R,RW	17	47.6
4	Oct. 12-13	88.50	3.75	2.9	17.6	R,RW,L	12	23.6
5	Aug. 26-27	78.75	3.15	2.6	20.6	RW,TRW,L	3	25.0
6	Mar. 4-5	78.65	2.75	2.1	22.8	S,SW,IP,ZR,R	17	28.6
7	Aug. 14-15	62.70	2.75	2.0	24.9	RW,TRW	4	22.8
8	Sep. 5-6	60.59	4.15	2.0	27.0	RW,TRW	5	14.6

1986

Rank	Date	Deposition Amount	$SO_4^=$ Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Sep. 10-11	211.82	8.90	7.2	7.2	R,RW,TRW	15	23.8
2	July 25-26	163.40	4.30	5.5	12.7	RW,TRW	7	38.0
3	July 12-13	85.88	1.90	2.9	15.7	RW,L	8	45.2
4	July 11-12	79.65	2.95	2.7	18.4	R,RW	15	27.0
5	Apr. 28-29	70.06	11.30	2.4	20.7	RW,TRW	4	6.2
6	June 11-12	66.25	2.65	2.3	23.0	R,RW,TRW	12	25.0
7	Sep. 15-16	65.00	3.25	2.2	25.1	R,RW	7	20.0

Table 6.2 - LONGWOODS (MOE)

NO_3^- Wet Deposition Episodes

(Units: Dep amt-mg/m^2, Concen-mg/l, Precip: dur-hr, amt-mm, type see text [page 13])

1985

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Aug. 23-24	32.40	1.78	6.0	6.0	R,RW	7	18.2
2	Sep. 7-8	24.86	0.42	4.6	10.6	RW,TRW	4	59.2
3	Oct. 18-19	18.09	0.38	3.4	13.9	R,RW	17	47.6
4	Dec. 10-11	10.01	1.82	1.8	15.8	S,R,L	15	5.5
5	Aug. 26-27	9.25	0.37	1.7	17.5	RW,TRW,L	3	25.0
6	Sep. 5-6	9.05	0.62	1.6	19.1	RW,TRW	5	14.6
7	Feb. 23-24	8.61	0.35	1.6	20.7	R,L	22	24.6
8	Feb. 26-27	8.50	0.85	1.6	22.3	S,R	10	10.0
9	Aug. 24-25	8.47	0.35	1.6	23.9	R,RW	13	24.2
10	Aug. 14-15	8.44	0.37	1.6	25.4	RW,TRW	4	22.8

1986

Rank	Date	Deposition Amount	NO_3^- Concen.	Ind. Dep.%	Cum. Dep.%	Prec. Type	Prec. Dur.	Prec. Amount
1	Sep. 10-11	16.18	0.68	3.4	3.4	R,RW,TRW	15	23.8
2	July 25-26	15.20	0.40	3.1	6.5	RW,TRW	7	38.0
3	Apr. 15-16	15.00	1.21	3.1	9.6	R,RW,L	6	12.4
4	Apr. 28-29	13.89	2.24	2.9	12.4	RW,TRW	4	6.2
5	Aug. 2-3	13.86	0.66	2.9	15.3	R,RW,TRW	3	21.0
6	July 12-13	11.75	0.26	2.4	17.7	RW,L	8	45.2
7	Apr. 20-21	10.75	0.43	2.2	19.9	R,RW,L	15	25.0
8	Apr. 7-8	10.40	1.13	2.1	22.1	RW,TRW,L	3	9.2
9	Mar. 5-6	9.67	0.93	2.0	24.1	S	12	10.4
10	June 11-12	9.50	0.38	2.0	26.0	R,RW,TRW	12	25.0

TABLE 7

SYMBOLS USED ON THE MAPS

ISOBAR

LOW PRESSURE CENTRE

HIGH PRESSURE CENTRE

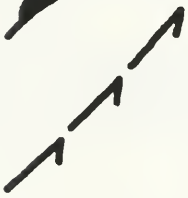
RIDGE OF HIGH PRESSURE

CENTRE OF HIGH OR LOW PRESSURE

HISTORY OF HIGH OR LOW PRESSURE CENTRE

COLD FRONT

WARM FRONT



TROWAL

WV

FRONTAL WAVE

AREA OF PRECIPITATION

AREA OF MIDDLE CLOUD

HAZE

MIST

FOG
-SKY INVISIBLE

FOG
- IN THE PAST HOUR

FOG
- SKY VISIBLE

DRIZZLE
- INTERMITTENT

DRIZZLE
- IN THE PAST HOUR

DRIZZLE
- CONTINUOUS
- LIGHT INTENSITY

RAIN
- INTERMITTENT

RAIN
- IN THE PAST HOUR

RAIN
- CONTINUOUS
- LIGHT INTENSITY

RAIN
- CONTINUOUS
- MODERATE INTENSITY

RAIN SHOWER(S)
-LIGHT INTENSITY

RAIN SHOWER(S)
- IN THE PAST HOUR
-LIGHT INTENSITY

THUNDERSTORM
- AT THE TIME OF OBSERVATION

THUNDERSTORM
- IN THE PAST HOUR

THUNDERSTORM
- IN THE PAST 6 HOURS

TABLE 8.1 $SO_4^=$ WET DEPOSITION - 1985-86

Number of Times Trajectories at Each Pressure Level Crossed Over Highest Emission Sources to Chalk River (11)**

Emission Sources		Pressure Level (mb)				Pressure Level (mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago	1	2	6	7	2	8	8
2	Illinois	0	0	4	5	0	6	6
3	Detroit	2	4	7	6	4	9	10
4	W. Virginia	1	3	4	1	3	4	6
5	Ohio *	1	4	3	0	4	3	6
6	Pennsylvania	1	5	3	0	5	3	6
7	Sudbury	2	3	5	5	4	5	6
8	Abitibi	1	3	3	1	3	3	3

* Includes Cleveland and other Ohio Areas

** No. of top 25% episodes (AES)

TABLE 8.2 NO_3^- WET DEPOSITION - 1985-86

Number of Times Trajectories at Each Pressure Level
Crossed Over Highest and High Emission Sources to Chalk River (15)**

Emission Sources		Pressure Level (mb)				Pressure Level(mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago *	1	3	7	8	3	10	11
2	Missouri	0	0	5	6	0	8	8
3	Detroit	3	5	8	7	6	11	13
4	Cleveland	4	8	7	3	9	7	12
5	W. Virginia	2	5	4	1	7	4	10
6	Ohio	3	6	4	1	8	4	10
7	Pennsylvania	4	8	4	1	9	4	10
8	Maryland	4	3	2	1	6	2	7
9	New Jersey	0	0	1	0	0	1	1
10	New York *	0	0	1	0	0	1	1

* Highest Emissions
** No. of top 25% episodes (AES)

TABLE 9.1 $SO_4^=$ WET DEPOSITION - 1985-86

Number of Times Trajectories at Each Pressure Level Crossed Over Highest Emission Sources to Dorset (15)**

Emission Sources		Pressure Level (mb)				Pressure Level (mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago	0	5	9	7	5	12	13
2	Illinois	0	2	5	5	2	7	8
3	Detroit	4	8	10	5	9	12	15
4	W. Virginia	2	7	6	0	8	6	9
5	Ohio *	1	8	5	1	9	5	10
6	Pennsylvania	3	6	4	0	7	4	9
7	Sudbury	5	3	6	5	6	7	8
8	Abitibi	2	1	0	0	2	0	2

* Includes Cleveland and other Ohio Areas

** No. of top 25% episodes (MOE)

TABLE 9.2 NO_3^- WET DEPOSITION - 1985-86

Number of Times Trajectories at Each Pressure Level
Crossed Over Highest and High Emission Sources to Dorset (22)**

Emission Sources		Pressure Level (mb)				Pressure Level(mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago *	2	10	13	12	10	17	21
2	Missouri	1	2	5	4	2	8	8
3	Detroit	9	12	12	7	14	12	20
4	Cleveland	6	10	5	1	11	5	12
5	W. Virginia	3	9	7	0	10	7	12
6	Ohio	2	9	5	1	10	5	12
7	Pennsylvania	4	6	4	0	8	4	12
8	Maryland	4	2	1	0	5	1	6
9	New Jersey	3	2	0	0	4	0	4
10	New York *	3	0	0	0	3	0	3

* Highest Emissions.
** No. of top 25% episodes (MOE)

TABLE 10.1 $SO_4^=$ WET DEPOSITION - 1985-86

Number of Times Trajectories at Each Pressure Level Crossed Over Highest Emission Sources to Longwoods (17)**

Emission Sources		Pressure Level (mb)				Pressure Level (mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago	1	7	13	14	7	14	14
2	Illinois	0	5	10	11	5	15	16
3	Detroit	9	15	16	11	16	16	17
4	W. Virginia	8	8	2	1	11	2	11
5	Ohio *	8	4	0	0	11	0	11
6	Pennsylvania	10	3	0	0	10	0	10
7	Sudbury	4	1	0	0	4	0	4
8	Abitibi	1	0	0	0	1	0	1

* Includes Cleveland and other Ohio Areas

** No. of top 25% episodes (AES/MOE)

TABLE 10.2 NO_3^- WET DEPOSITION - 1985-86

Number of Times Trajectories at Each Pressure Level
Crossed Over Highest and High Emission Sources to Longwoods (24)**

Emission Sources		Pressure Level (mb)				Pressure Level(mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago *	3	10	14	16	11	17	19
2	Missouri	0	4	13	10	4	16	17
3	Detroit	13	18	20	14	19	20	22
4	Cleveland	15	15	8	4	20	8	21
5	W. Virginia	8	9	2	3	14	4	15
6	Ohio	10	4	3	3	13	3	14
7	Pennsylvania	10	4	1	2	11	2	12
8	Maryland	2	1	1	0	3	1	4
9	New Jersey	1	0	1	0	1	1	2
10	New York *	0	1	0	0	1	0	1

* Highest Emissions

** No. of top 25% episodes (AES/MOE)

TABLE 11.1 $SO_4^=$ WET DEPOSITION - 1985-88

Number of Times Trajectories at Each Pressure Level Crossed Over Highest Emission Sources to Chalk River (20)**

Emission Sources		Pressure Level (mb)				Pressure Level (mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago	3	5	13	15	5	16	16
2	Illinois	0	1	10	11	1	13	13
3	Detroit	4	11	12	8	11	14	18
4	W. Virginia	1	8	5	2	8	5	12
5	Ohio *	2	7	5	1	8	5	12
6	Pennsylvania	3	6	5	0	7	5	9
7	Sudbury	3	9	13	13	10	13	14
8	Abitibi	2	4	4	1	4	4	4

* Includes Cleveland and other Ohio Areas

** No. of top 25% episodes (AES)

TABLE 11.2 NO_3^- WET DEPOSITION - 1985-88

Number of Times Trajectories at Each Pressure Level
Crossed Over Highest and High Emission Sources to Chalk River (31)**

Emission Sources		Pressure Level (mb)				Pressure Level(mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago *	5	7	20	19	9	24	25
2	Missouri	0	1	13	14	1	18	18
3	Detroit	8	14	15	12	18	21	28
4	Cleveland	8	16	7	4	19	8	23
5	W. Virginia	2	12	5	1	14	5	18
6	Ohio	5	11	4	1	15	4	17
7	Pennsylvania	9	14	5	1	16	5	18
8	Maryland	9	3	2	1	11	2	12
9	New Jersey	2	0	2	0	2	2	4
10	New York *	2	1	1	0	3	1	4

* Highest Emissions

** No. of top 25% episodes (AES)

TABLE 12.1 $SO_4^=$ WET DEPOSITION - 1985-88

Number of Times Trajectories at Each Pressure Level Crossed Over Highest Emission Sources to Longwoods (28)**

Emission Sources		Pressure Level (mb)				Pressure Level (mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago	4	13	20	20	13	22	23
2	Illinois	0	11	15	18	11	24	26
3	Detroit	14	24	25	20	25	26	28
4	W. Virginia	13	12	4	2	18	4	18
5	Ohio *	14	7	1	1	17	1	17
6	Pennsylvania	15	5	1	1	15	1	15
7	Sudbury	4	2	0	0	5	0	5
8	Abitibi	1	0	0	0	1	0	1

* Includes Cleveland and other Ohio Areas

** No. of top 25% episodes (AES/MOE)

TABLE 12.2 NO_3^- WET DEPOSITION - 1985-88

Number of Times Trajectories at Each Pressure Level
Crossed Over Highest and High Emission Sources to Longwoods (39)**

Emission Sources		Pressure Level (mb)				Pressure Level(mb)		Pressure Level
No.	Name	1000	925	850	700	Low (1000-925)	High (850-700)	Any
1	Chicago *	9	17	23	24	18	28	32
2	Missouri	0	10	18	17	10	26	28
3	Detroit	21	30	34	25	31	34	37
4	Cleveland	23	26	15	10	34	16	35
5	W. Virginia	14	16	6	5	24	8	26
6	Ohio	17	8	5	4	21	5	23
7	Pennsylvania	16	6	3	4	17	4	19
8	Maryland	4	2	1	0	5	1	6
9	New Jersey	2	0	1	0	2	1	3
10	New York *	1	1	0	0	2	0	2

* Highest Emissions

** No. of top 25% episodes (AES/MOE)

Map of Air Quality Stations

FIGURE 1

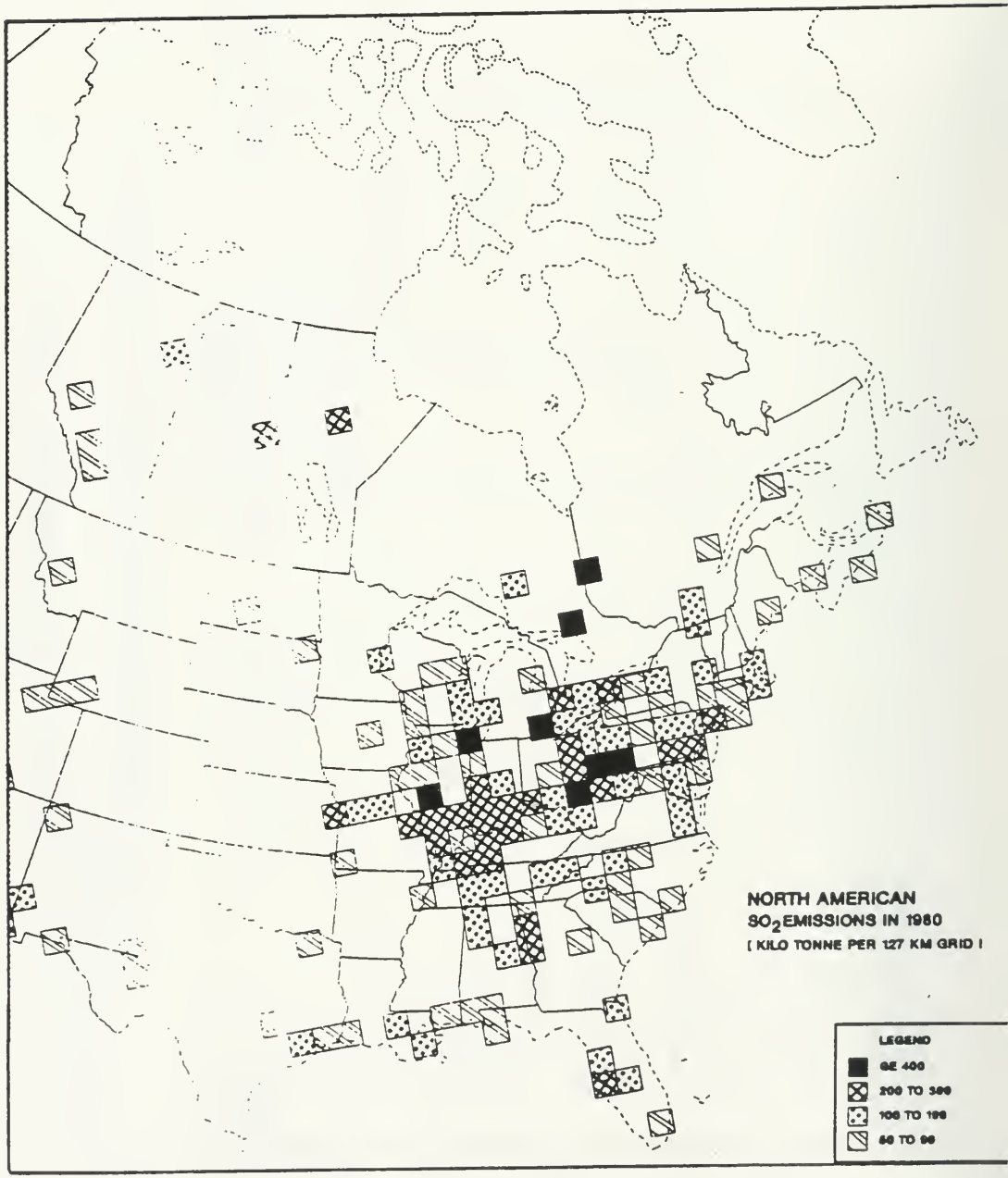

NORTH AMERICAN
SO_2 EMISSIONS IN 1980
(KILO TONNE PER 127 KM GRID)
LEGEND
GE 400
200 TO 399
100 TO 199
50 TO 99

FIGURE 2

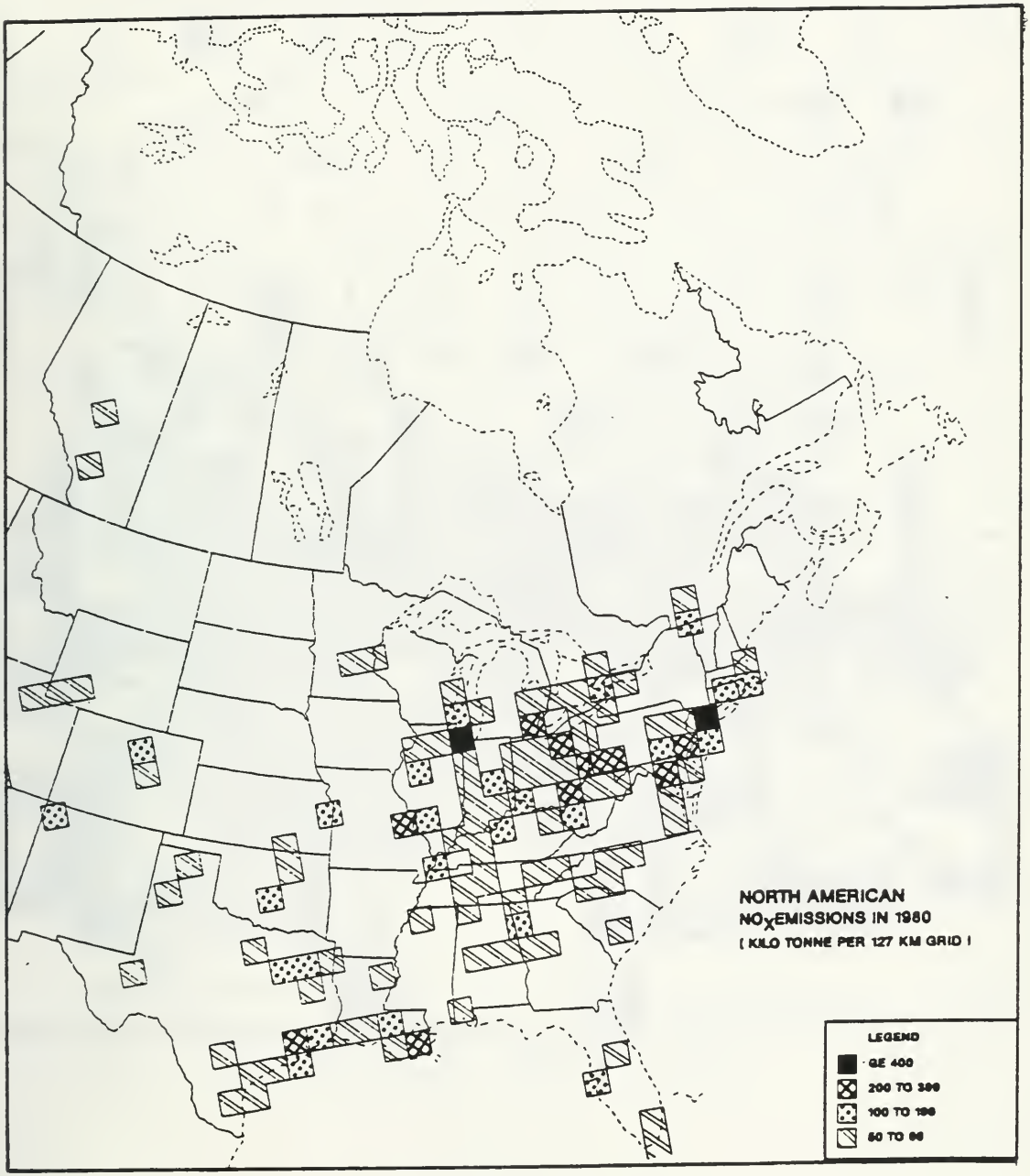

NORTH AMERICAN
NOx EMISSIONS IN 1980
(KILO TONNE PER 127 KM GRID)
LEGEND
GE 400
200 TO 399
100 TO 199
50 TO 99

FIGURE 3

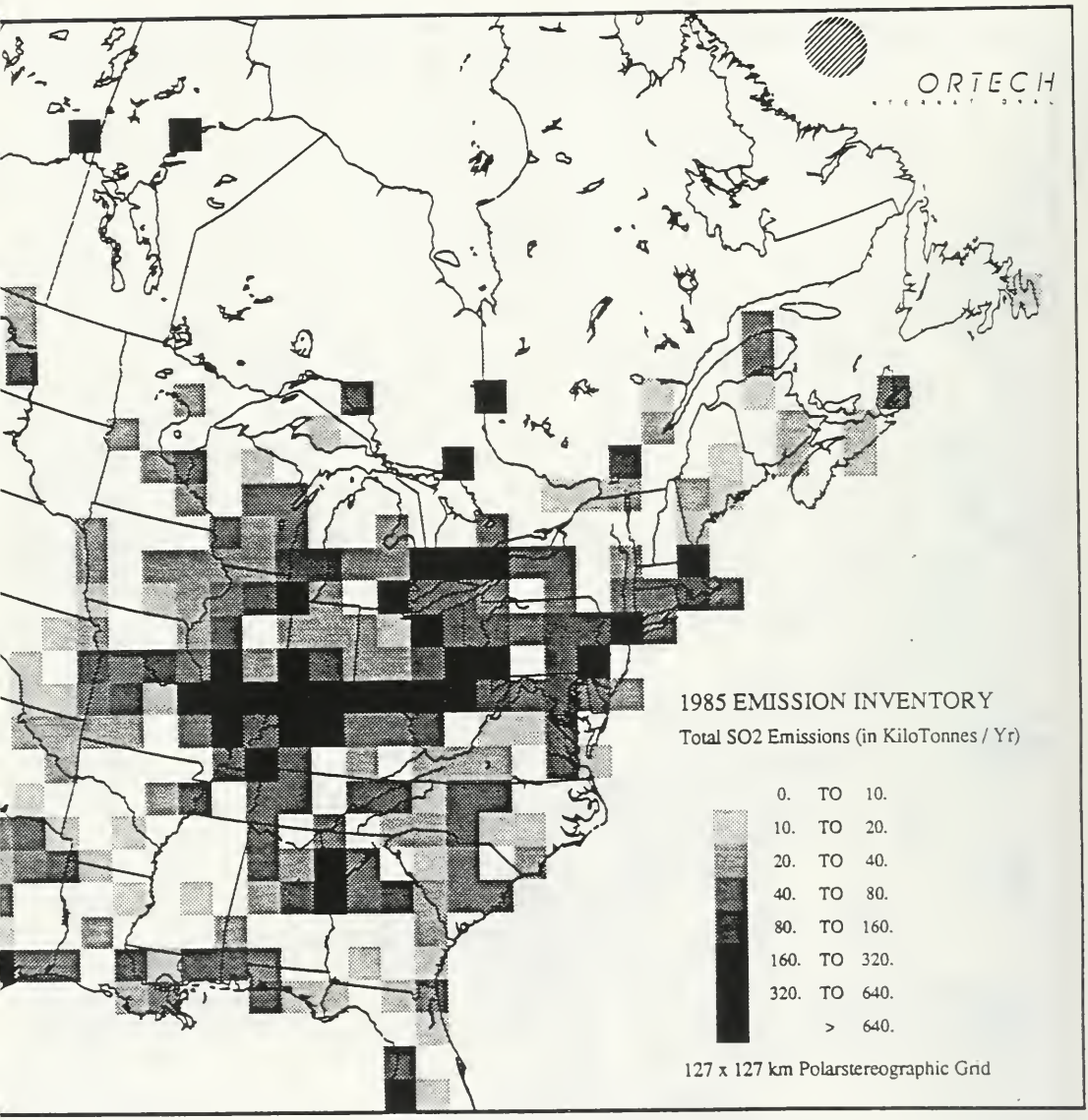

ORTECH
1985 EMISSION INVENTORY
Total SO2 Emissions (in KiloTonnes / Yr)
0. TO 10.
10. TO 20.
20. TO 40.
40. TO 80.
80. TO 160.
160. TO 320.
320. TO 640.
> 640.
127 x 127 km Polarstereographic Grid

FIGURE 4

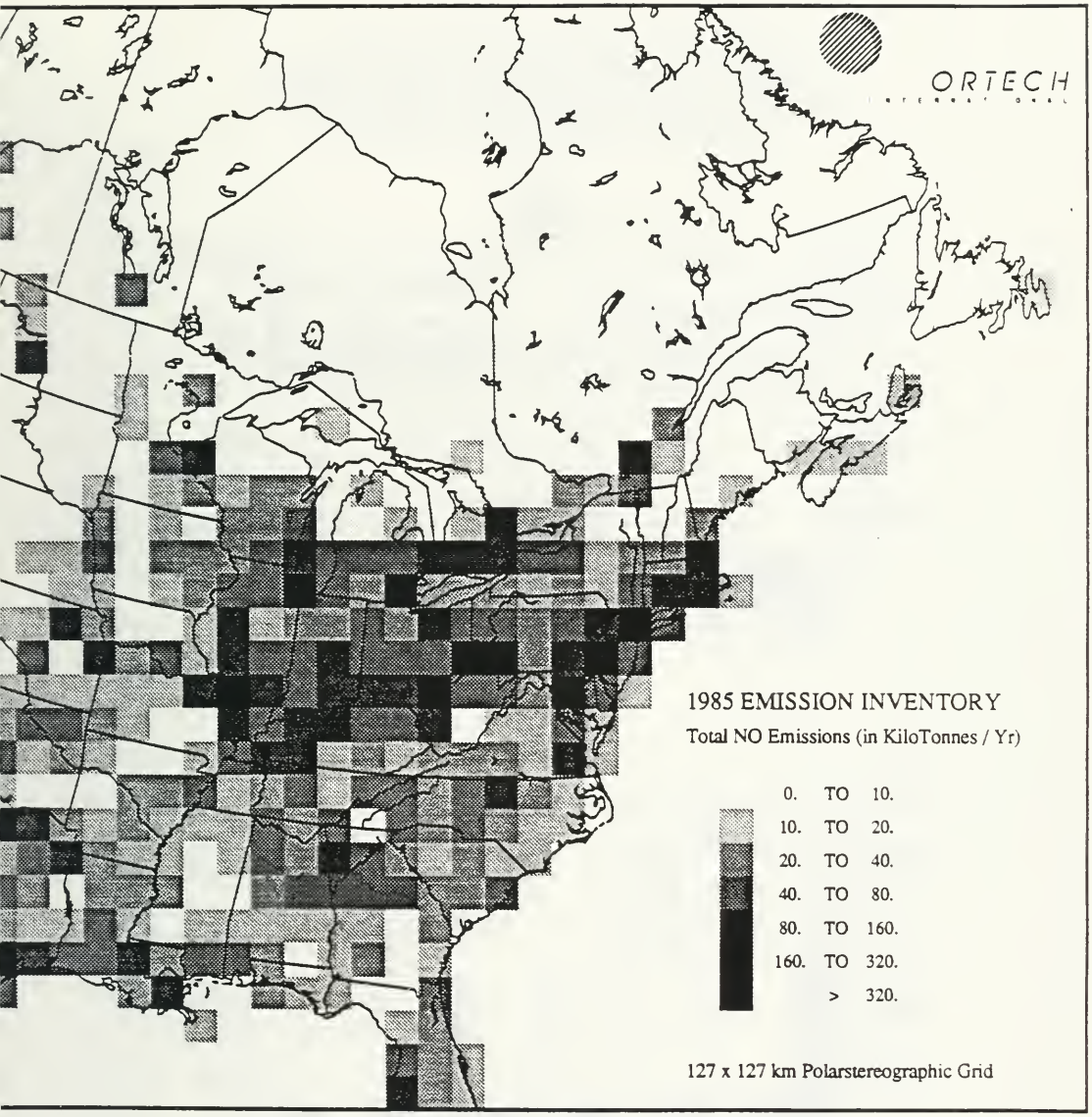

ORTECH
1985 EMISSION INVENTORY
Total NO Emissions (in KiloTonnes / Yr)
0. TO 10.
10. TO 20.
20. TO 40.
40. TO 80.
80. TO 160.
160. TO 320.
> 320.
127 x 127 km Polarstereographic Grid

FIGURE 5

Rank Versus Precipitation Type
Top 25% $SO_4^=$ Wet Deposition Episodes
CHALK RIVER (AES) - 1985-86

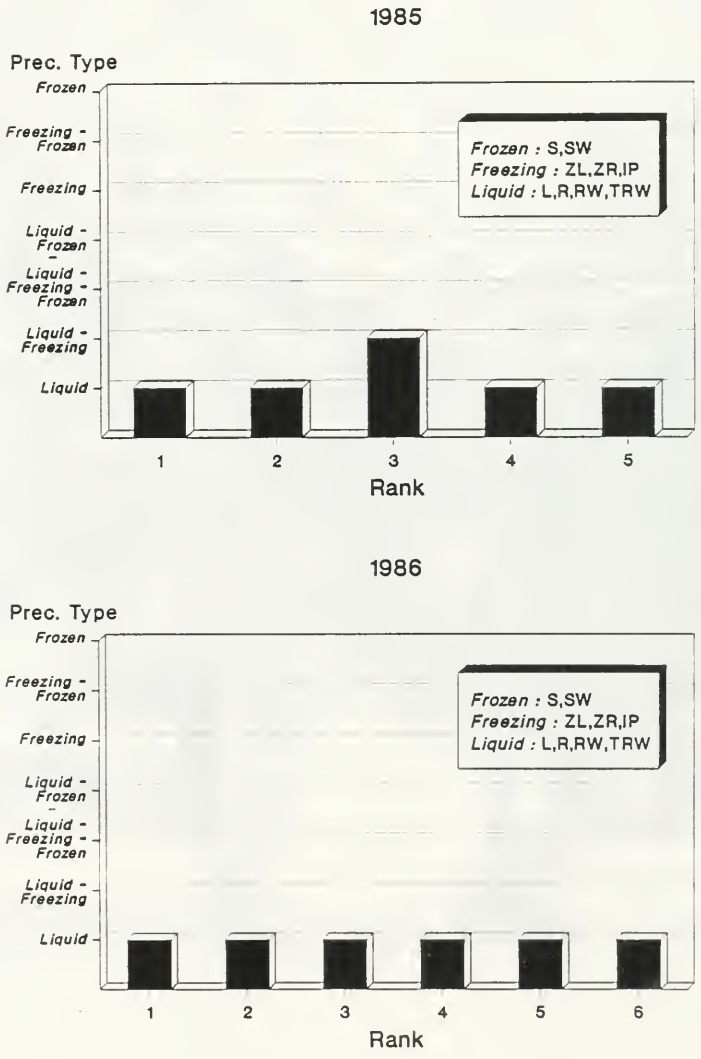


FIGURE 6.1

Rank Versus Precipitation Type
Top 25% NO_3^- Wet Deposition Episodes
CHALK RIVER (AES) - 1985-86

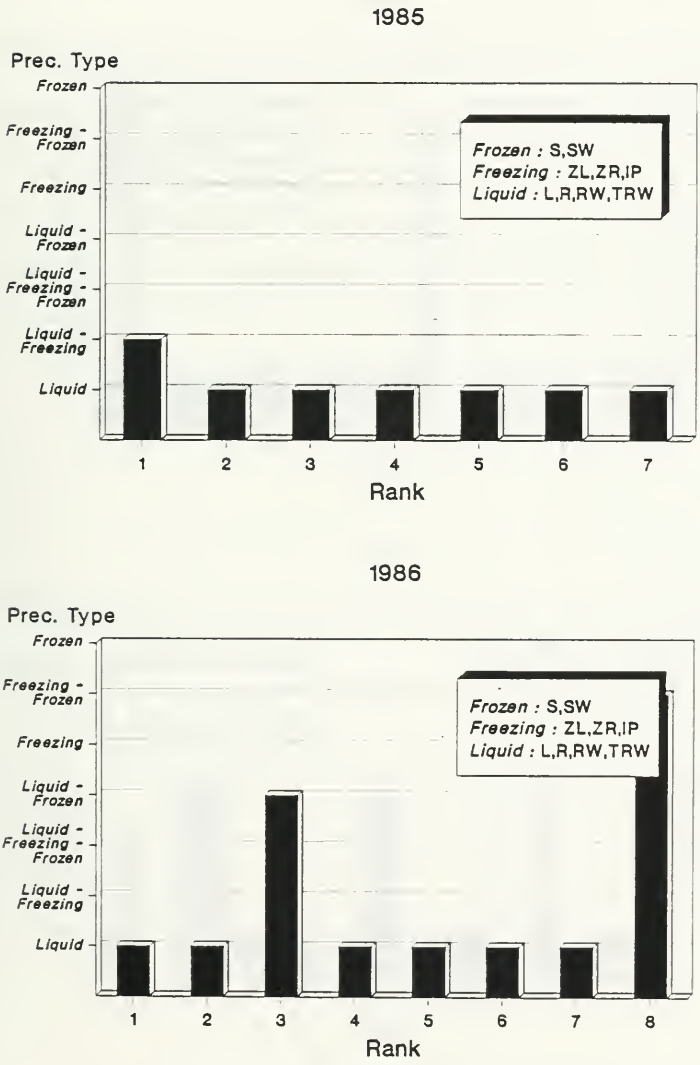


FIGURE 6.2

Rank Versus Precipitation Type
Top 25% $SO_4^=$ Wet Deposition Episodes
DORSET (MOE) - 1985-86

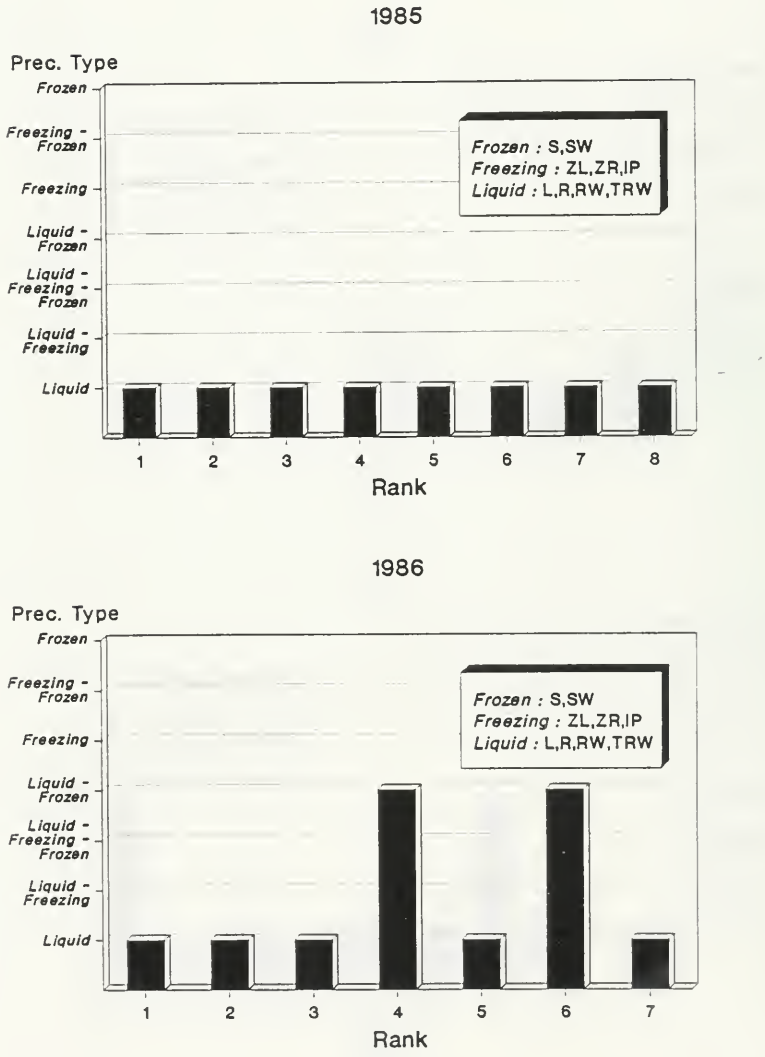


FIGURE 7.1

Rank Versus Precipitation Type
Top 25% NO_3^- Wet Deposition Episodes
DORSET (MOE) - 1985-86

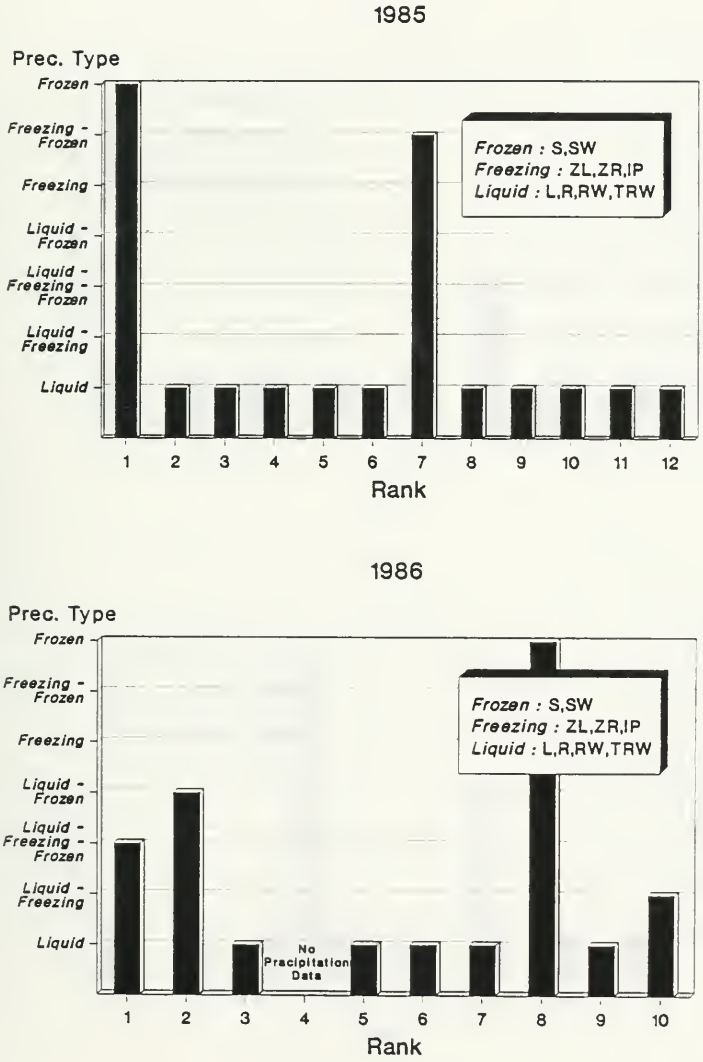


FIGURE 7.2

Rank Versus Precipitation Type
Top 25% $SO_4^=$ Wet Deposition Episodes
LONGWOODS (AES) - 1985-86

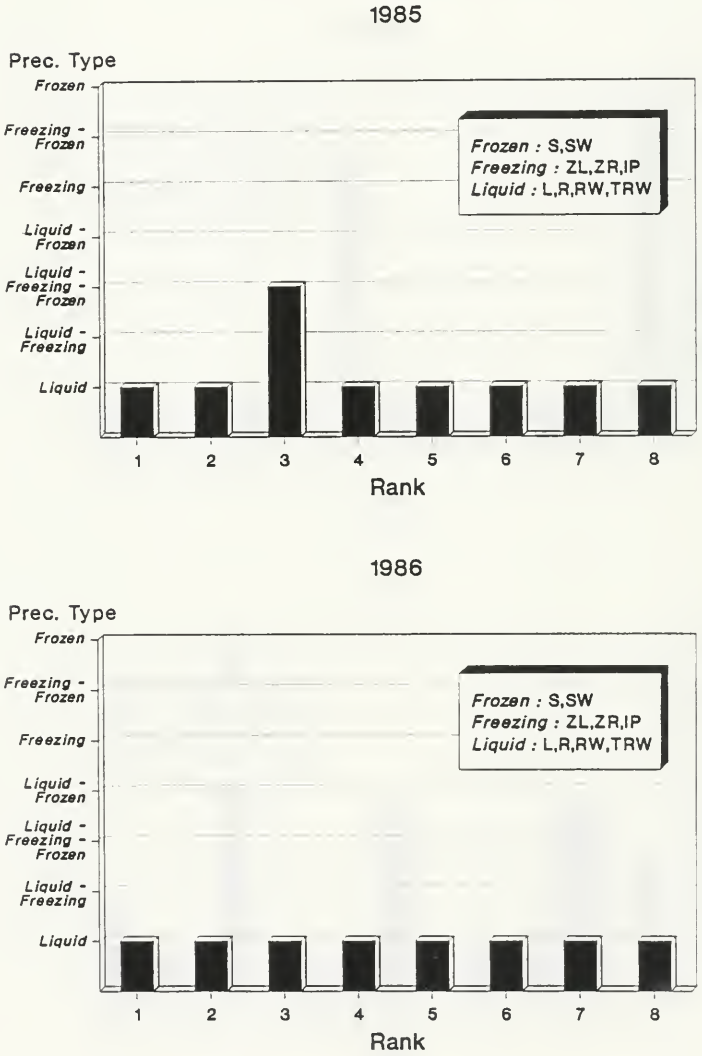


FIGURE 8.1

Rank Versus Precipitation Type
Top 25% NO_3^- Wet Deposition Episodes
LONGWOODS (AES) - 1985-86

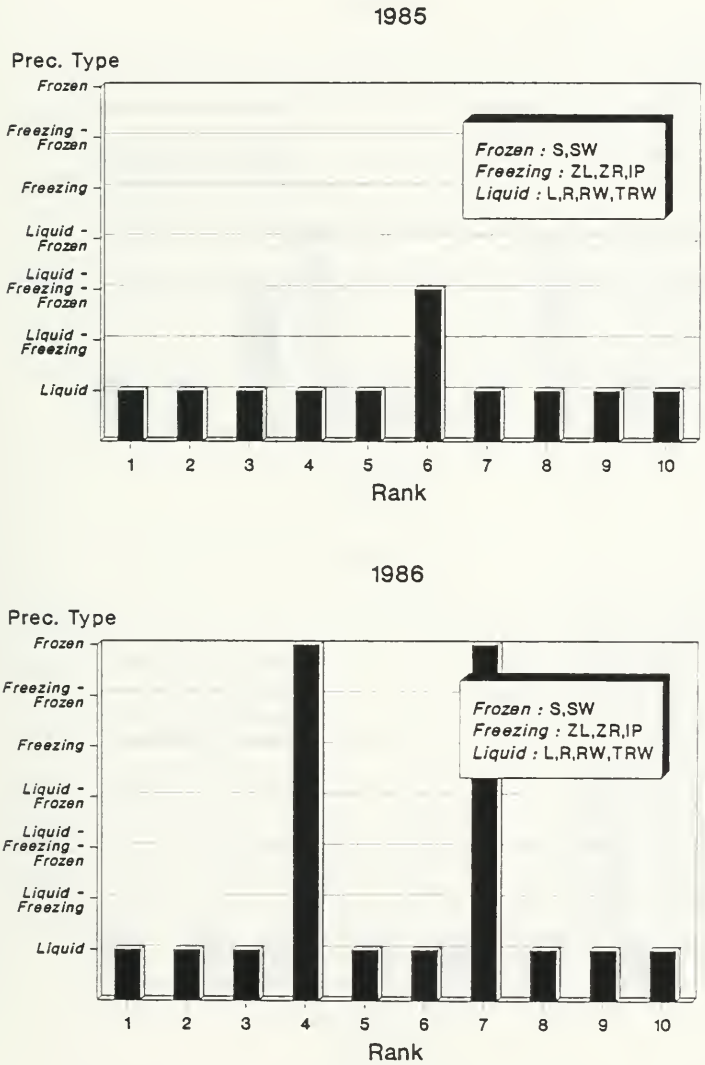


FIGURE 8.2

Rank Versus Precipitation Type
Top 25% $SO_4^=$ Wet Deposition Episodes
LONGWOODS (MOE) - 1985-86

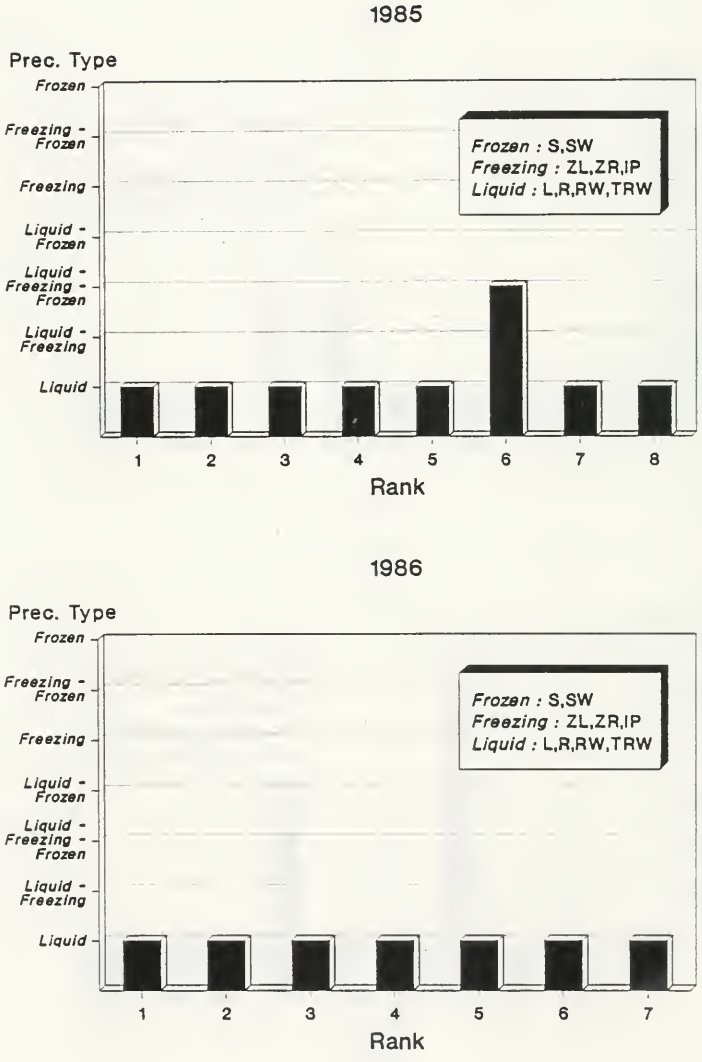
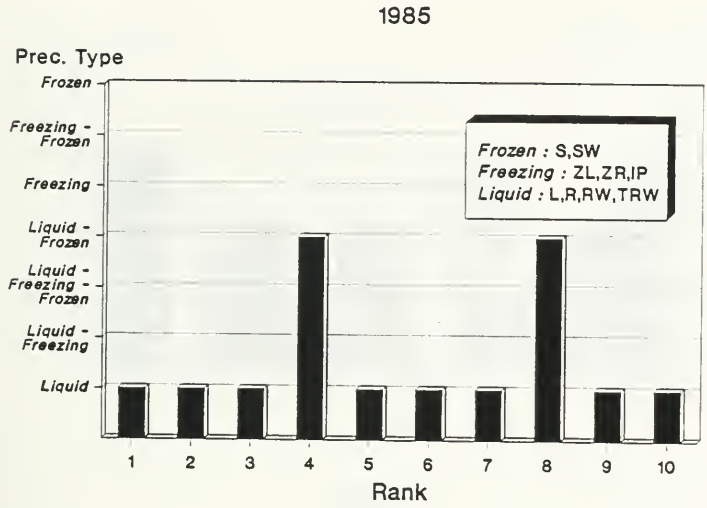


FIGURE 9.1

Rank Versus Precipitation Type
Top 25% NO_3^- Wet Deposition Episodes
LONGWOODS (MOE) - 1985-86



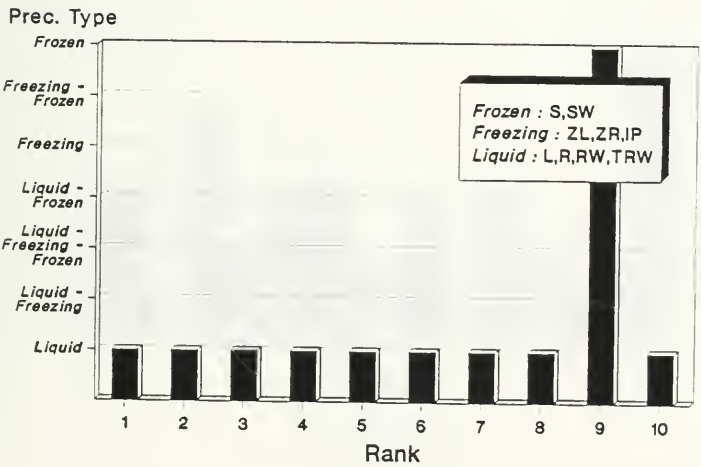
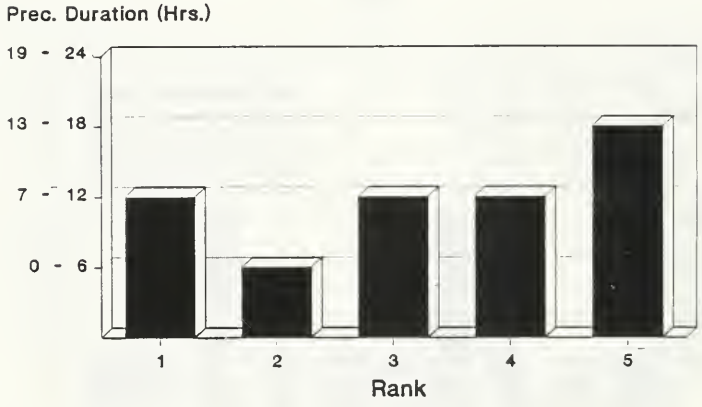


FIGURE 9.2

Rank Versus Precipitation Duration
Top 25% $SO_4^=$ Wet Deposition Episodes
CHALK RIVER (AES) - 1985-86

1985



1986

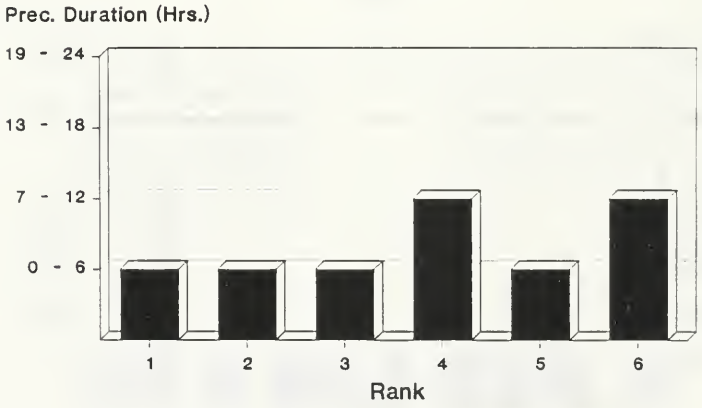
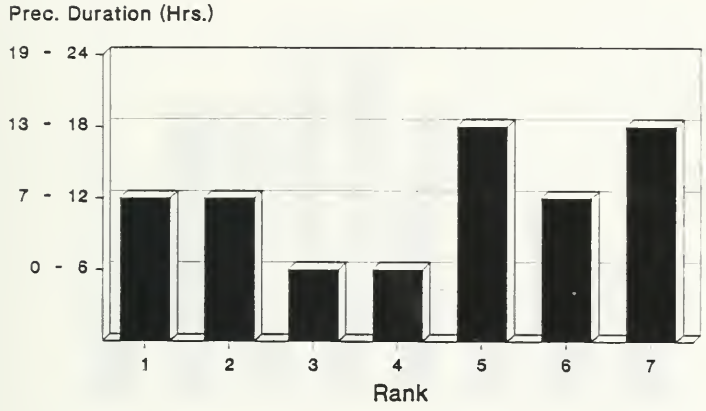


FIGURE 10.1

Rank Versus Precipitation Duration
Top 25% NO_3^- Wet Deposition Episodes
CHALK RIVER (AES) - 1985-86

1985



1986

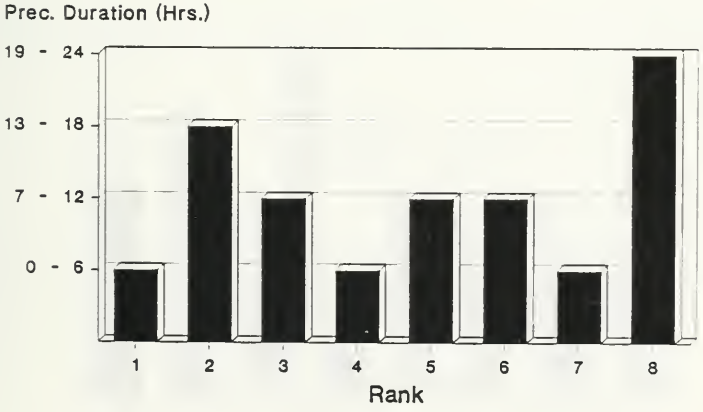


FIGURE 10.2

Rank Versus Precipitation Duration
Top 25% $SO_4^=$ Wet Deposition Episodes
LONGWOODS (AES) - 1985-86

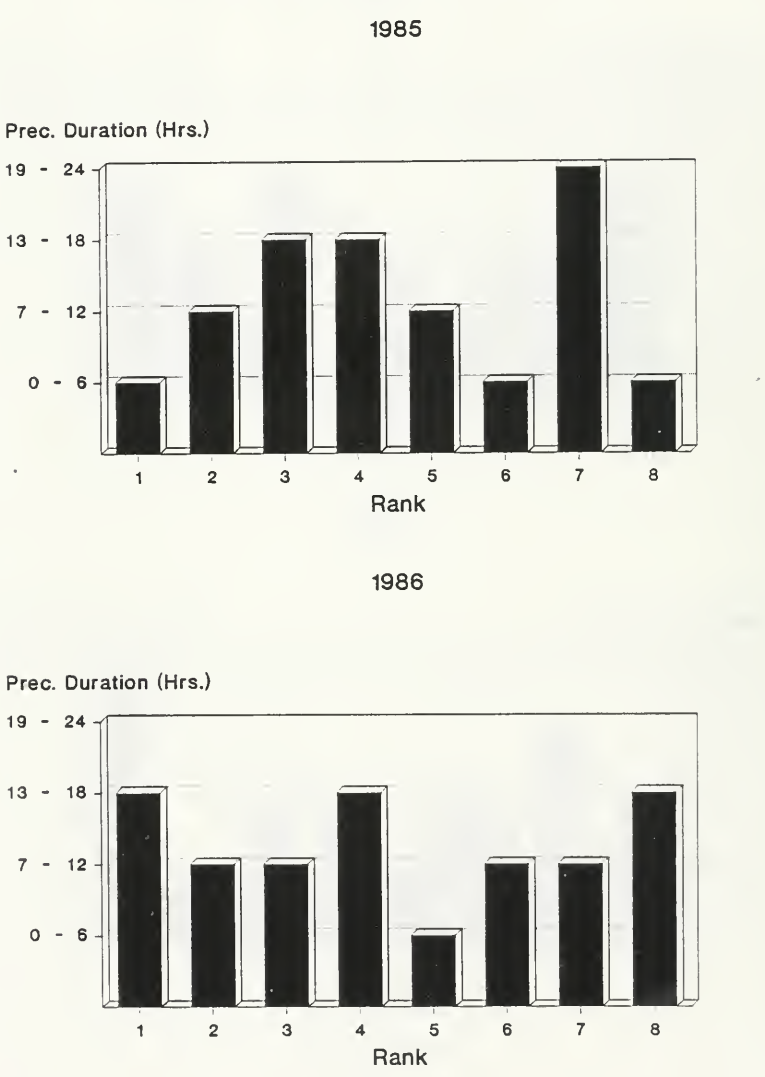
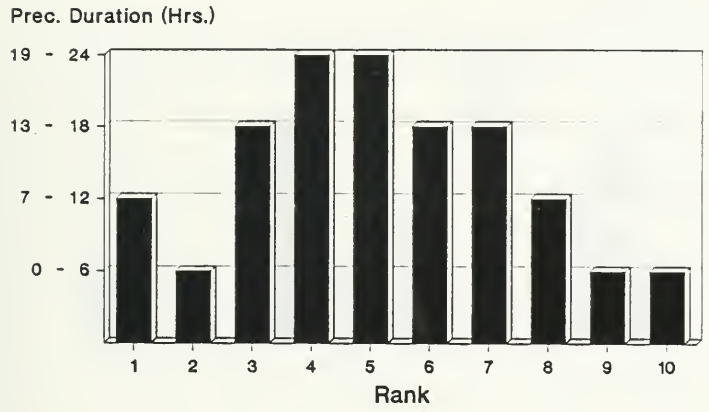


FIGURE 11.1

Rank Versus Precipitation Duration
Top 25% NO_3^- Wet Deposition Episodes
LONGWOODS (AES) - 1985-86

1985



1986

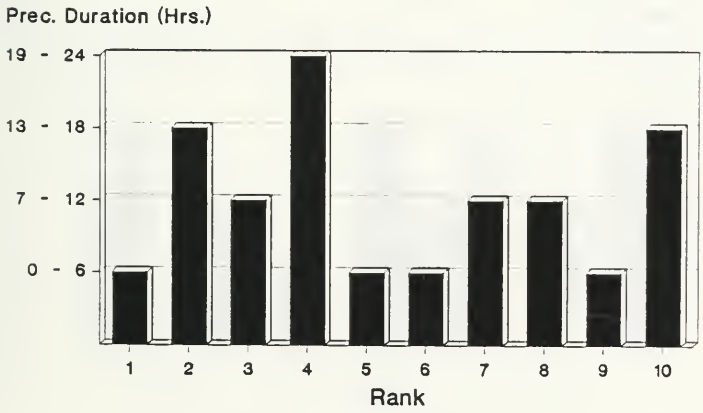
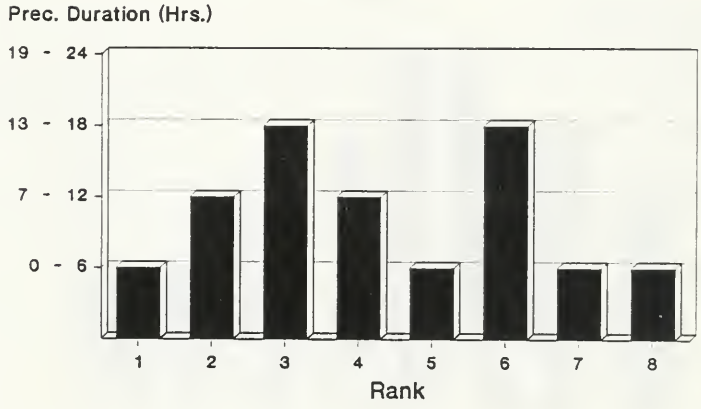


FIGURE 11.2

Rank Versus Precipitation Duration
Top 25% $SO_4^=$ Wet Deposition Episodes
LONGWOODS (MOE) - 1985-86

1985



1986

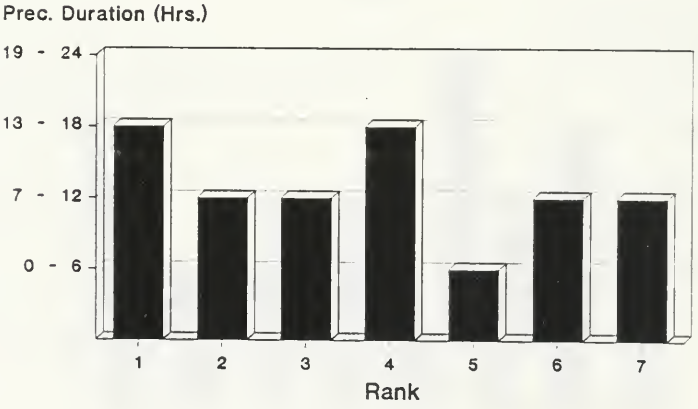
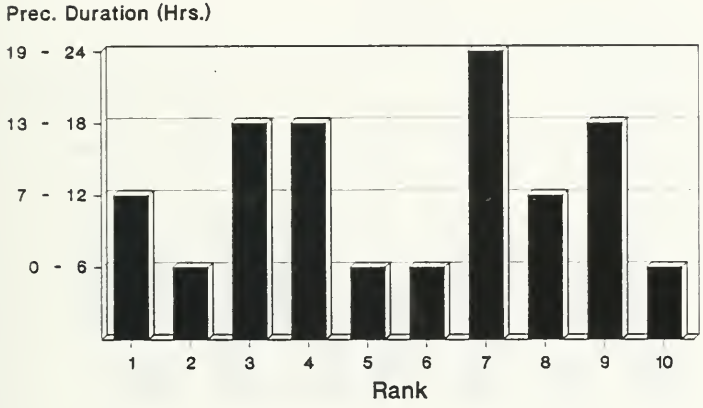


FIGURE 12.1

Rank Versus Precipitation Duration
Top 25% NO_3^- Wet Deposition Episodes
LONGWOODS (MOE) - 1985-86

1985



1986

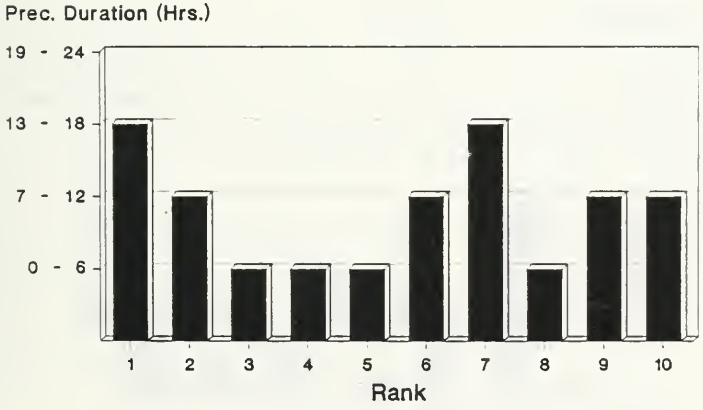
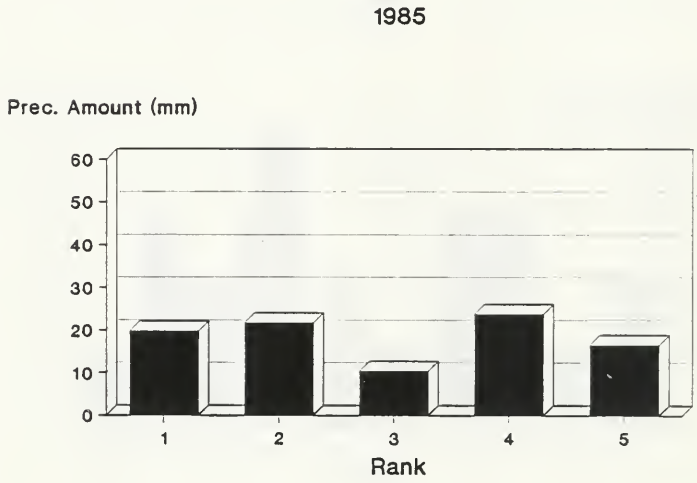


FIGURE 12.2

Rank Versus Precipitation Amount
Top 25% $SO_4^=$ Wet Deposition Episodes
CHALK RIVER (AES) - 1985-86



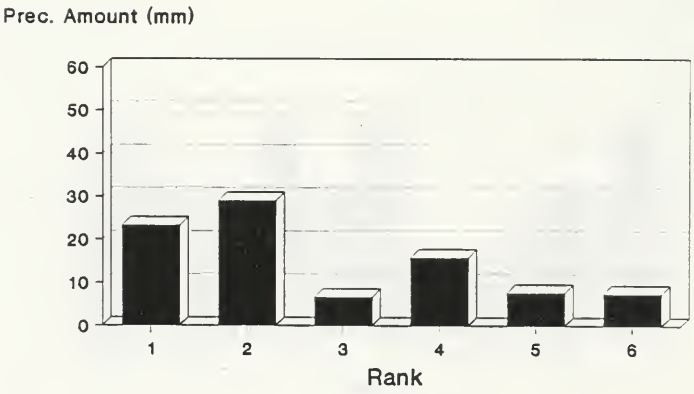


FIGURE 13.1

Rank Versus Precipitation Amount
Top 25% NO_3^- Wet Deposition Episodes
CHALK RIVER (AES) - 1985-86

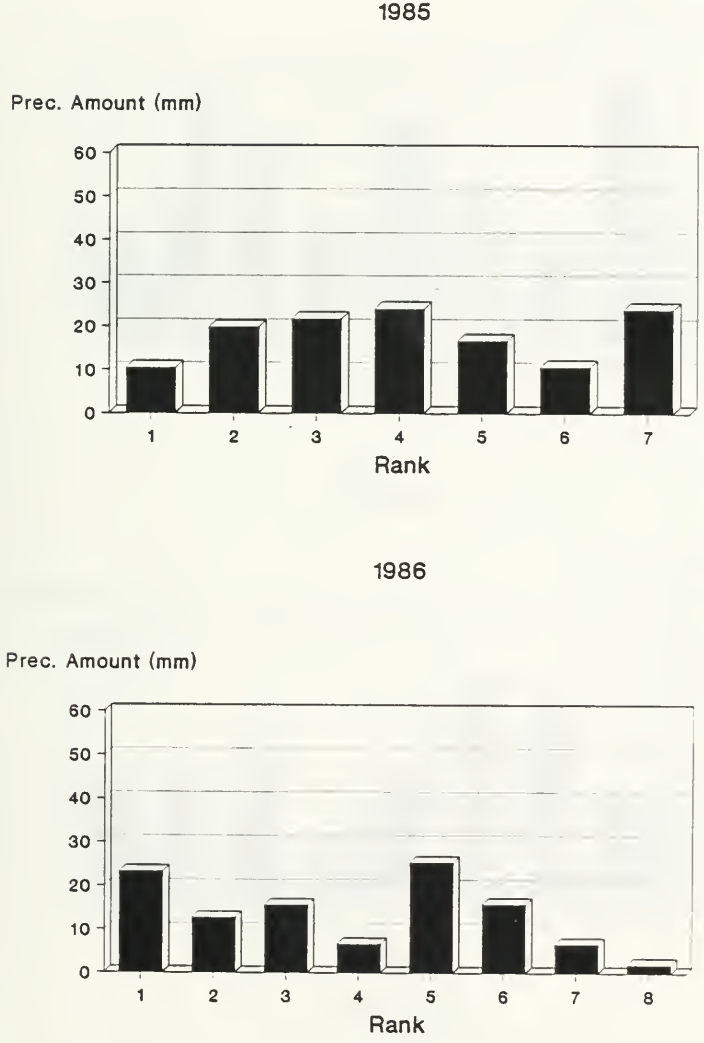
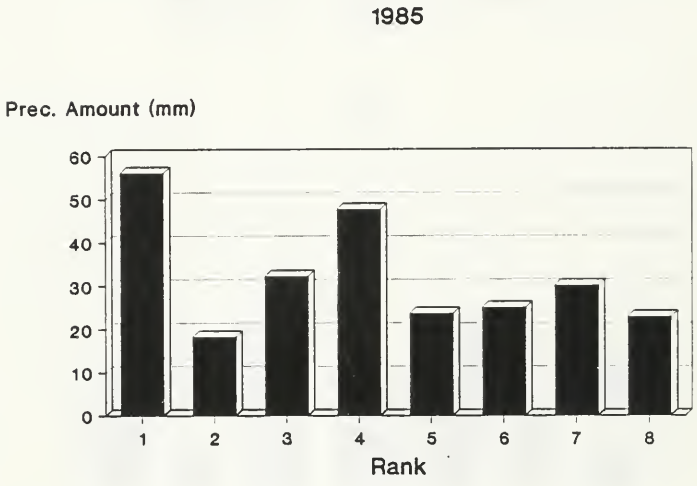


FIGURE 13.2

Rank Versus Precipitation Amount
Top 25% $SO_4^=$ Wet Deposition Episodes
LONGWOODS (AES) - 1985-86



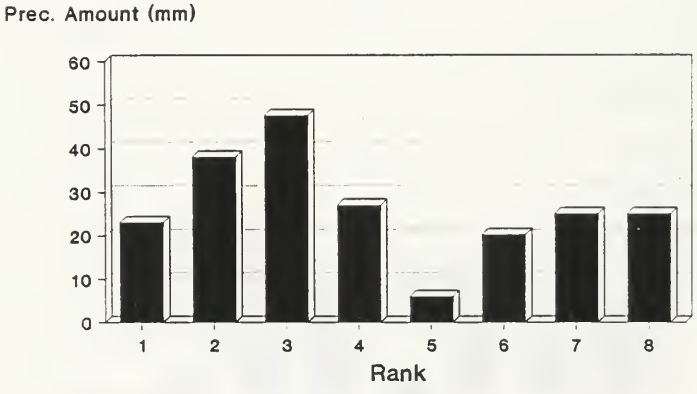
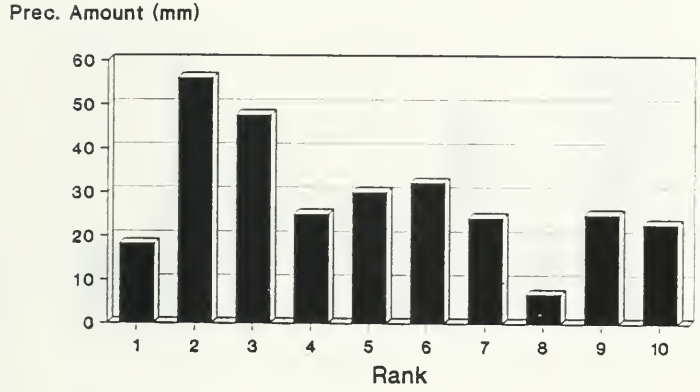


FIGURE 14.1

Rank Versus Precipitation Amount
Top 25% NO_3^- Wet Deposition Episodes
LONGWOODS (AES) - 1985-86

1985



1986

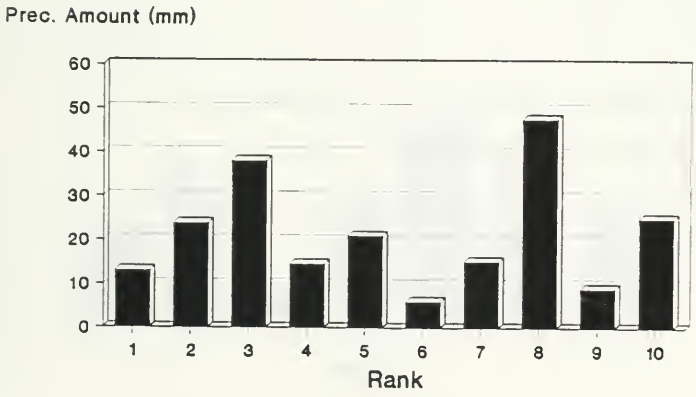
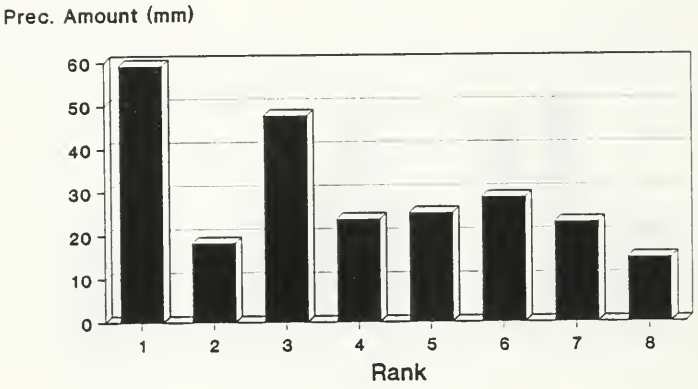


FIGURE 14.2

Rank Versus Precipitation Amount
Top 25% $SO_4^=$ Wet Deposition Episodes
LONGWOODS (MOE) - 1985-86

1985



1986

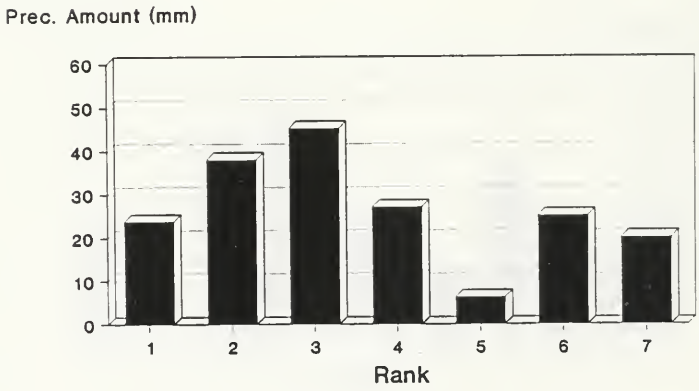


FIGURE 15.1

Rank Versus Precipitation Amount
Top 25% NO_3^- Wet Deposition Episodes
LONGWOODS (MOE) - 1985-86

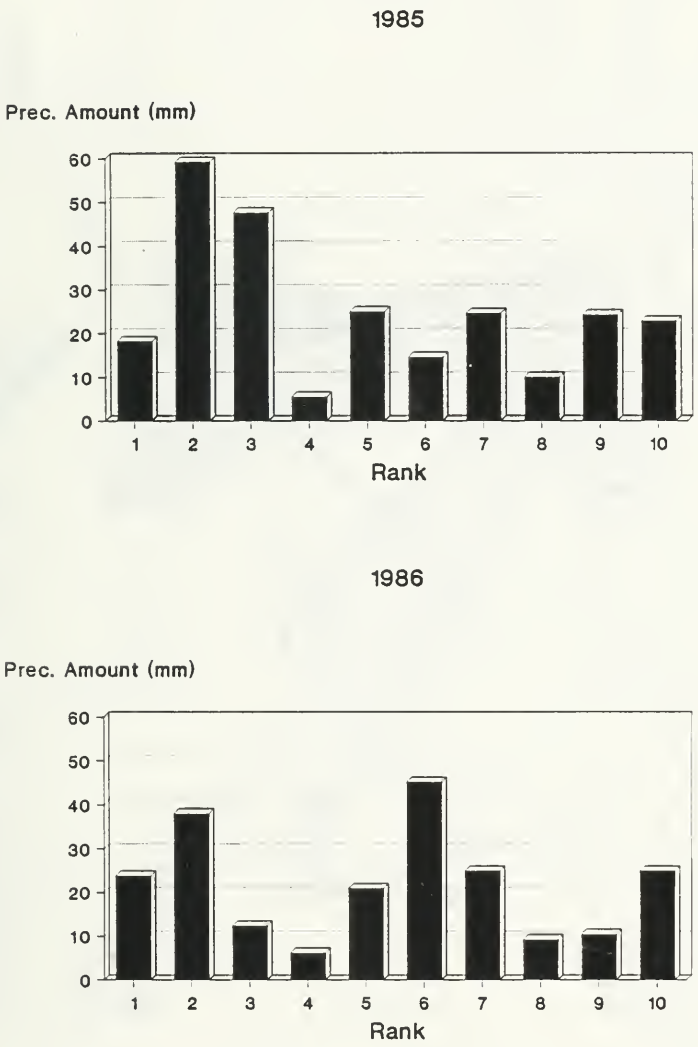


FIGURE 15.2

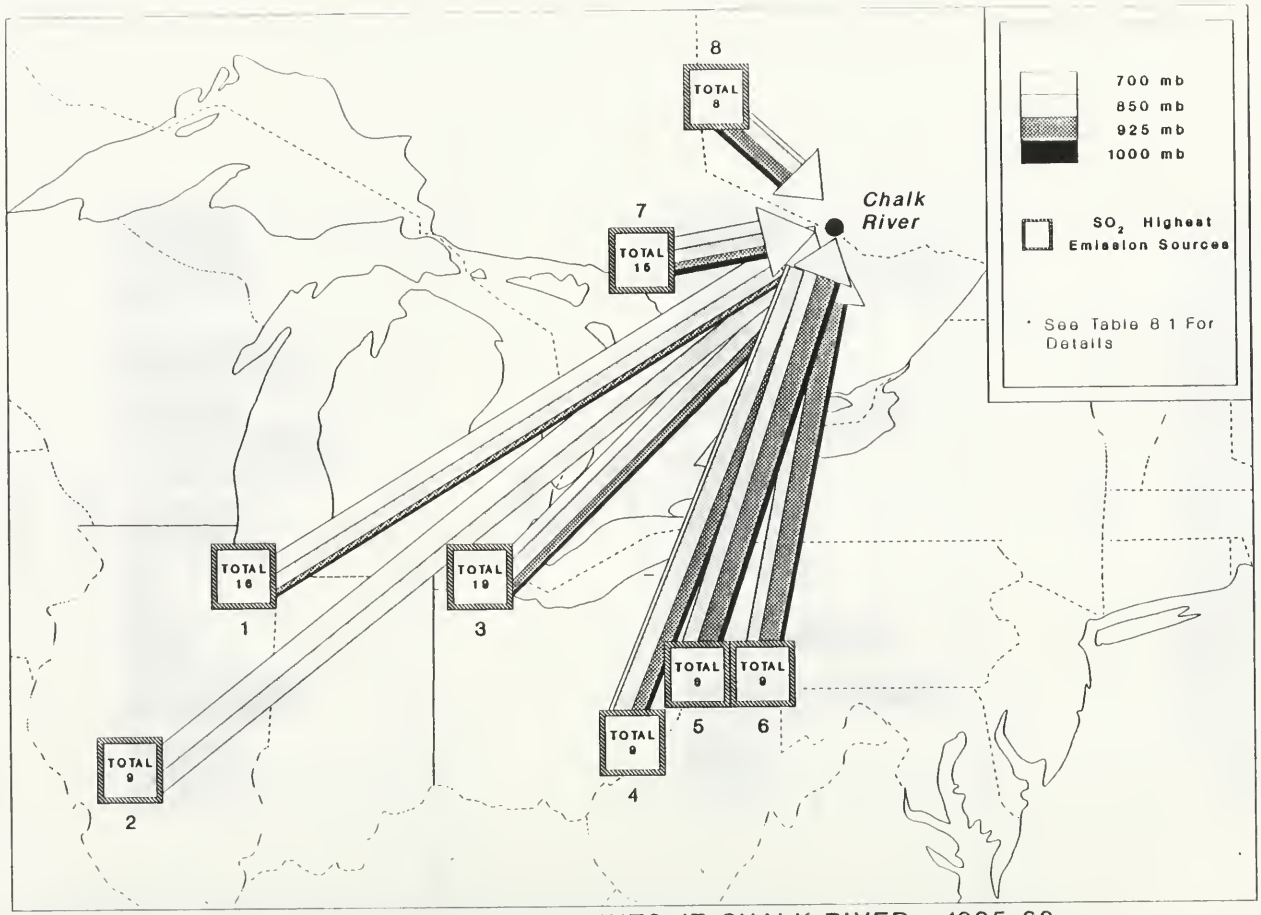


Figure 16.1 SO_4^{--} WET DEPOSITION EVENTS AT CHALK RIVER - 1985-86

TRANSPORT AT EACH PRESSURE LEVEL

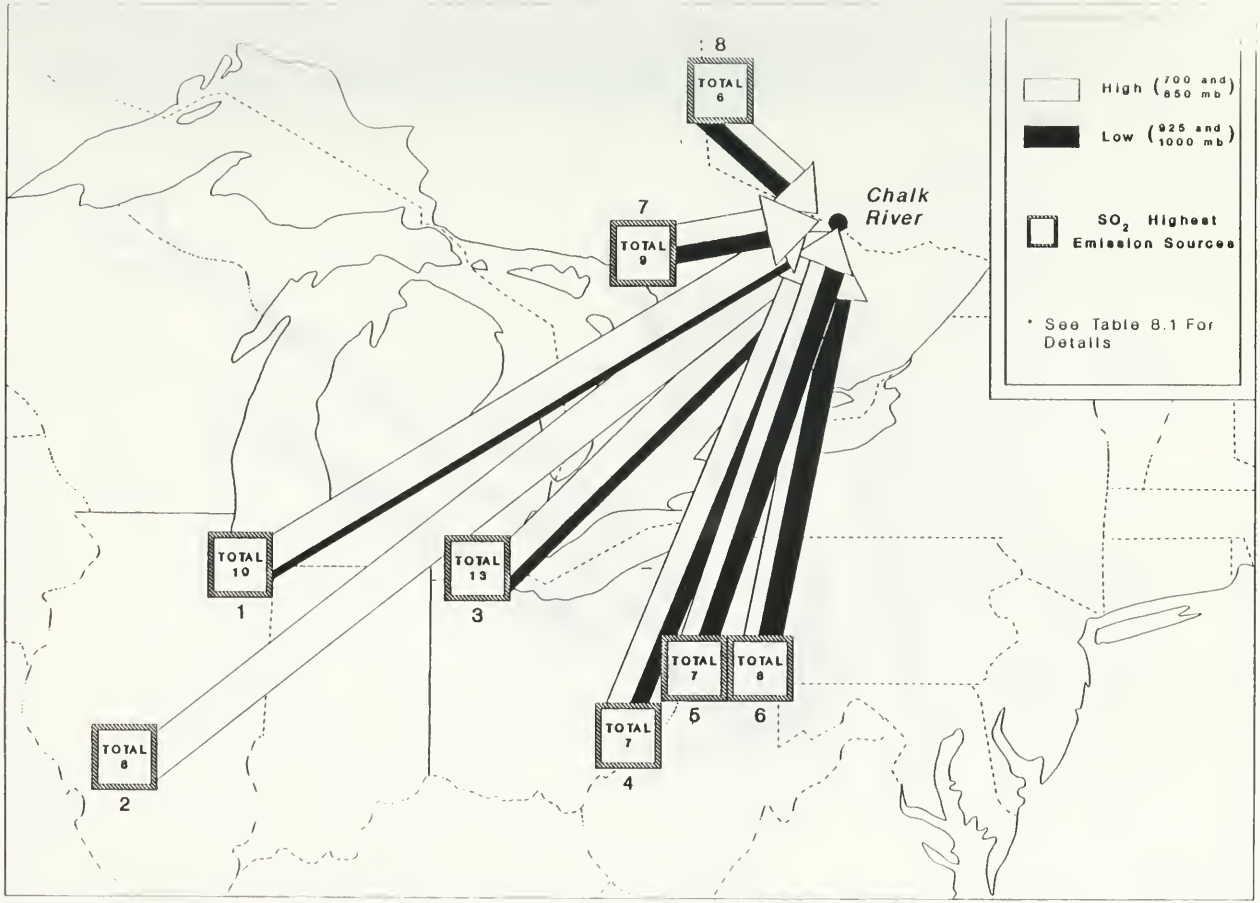


Figure 16.2 SO_4^{--} WET DEPOSITION EVENTS AT CHALK RIVER - 1985-86

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

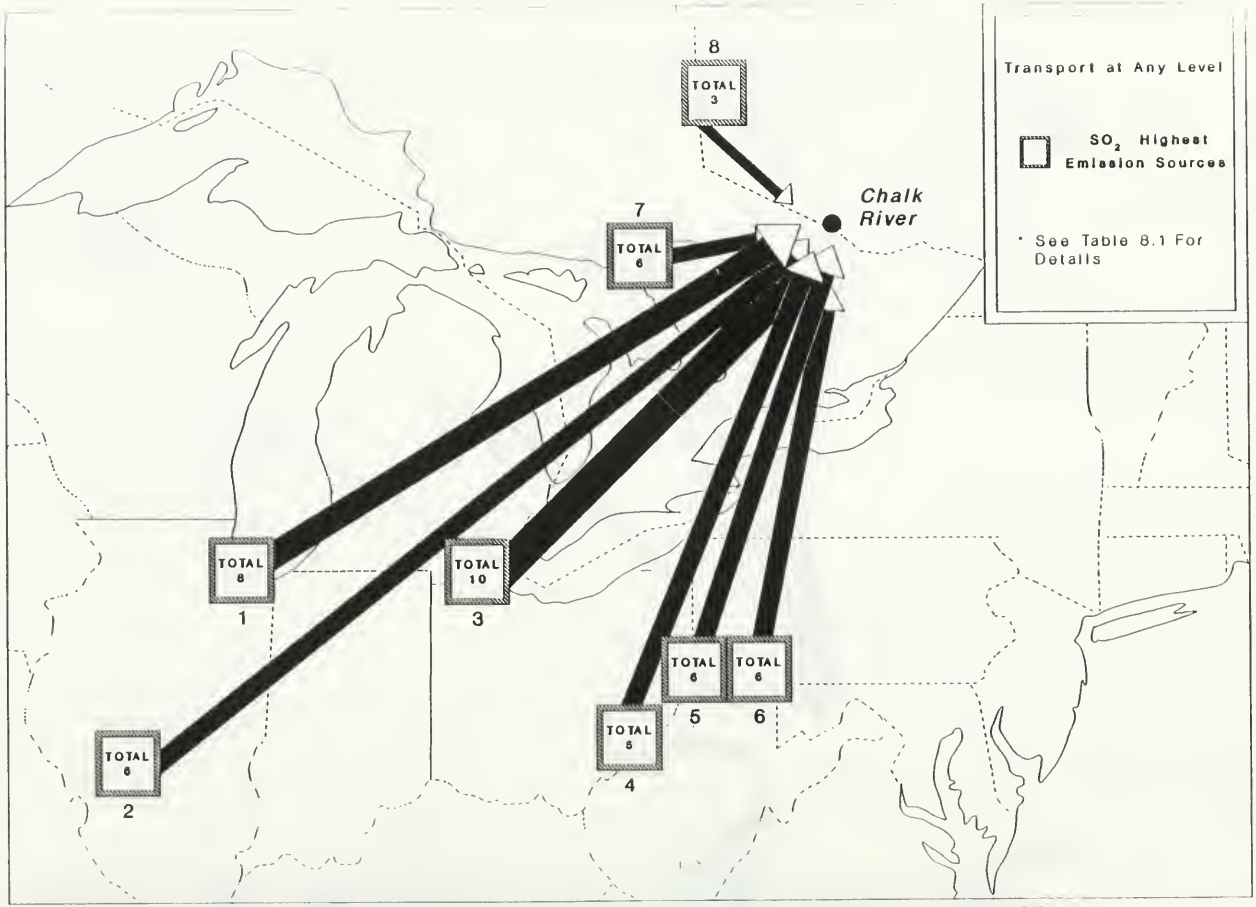


Figure 16.3 SO_4^{--} WET DEPOSITION EVENTS AT CHALK RIVER - 1985-86

TRANSPORT AT ANY PRESSURE LEVEL

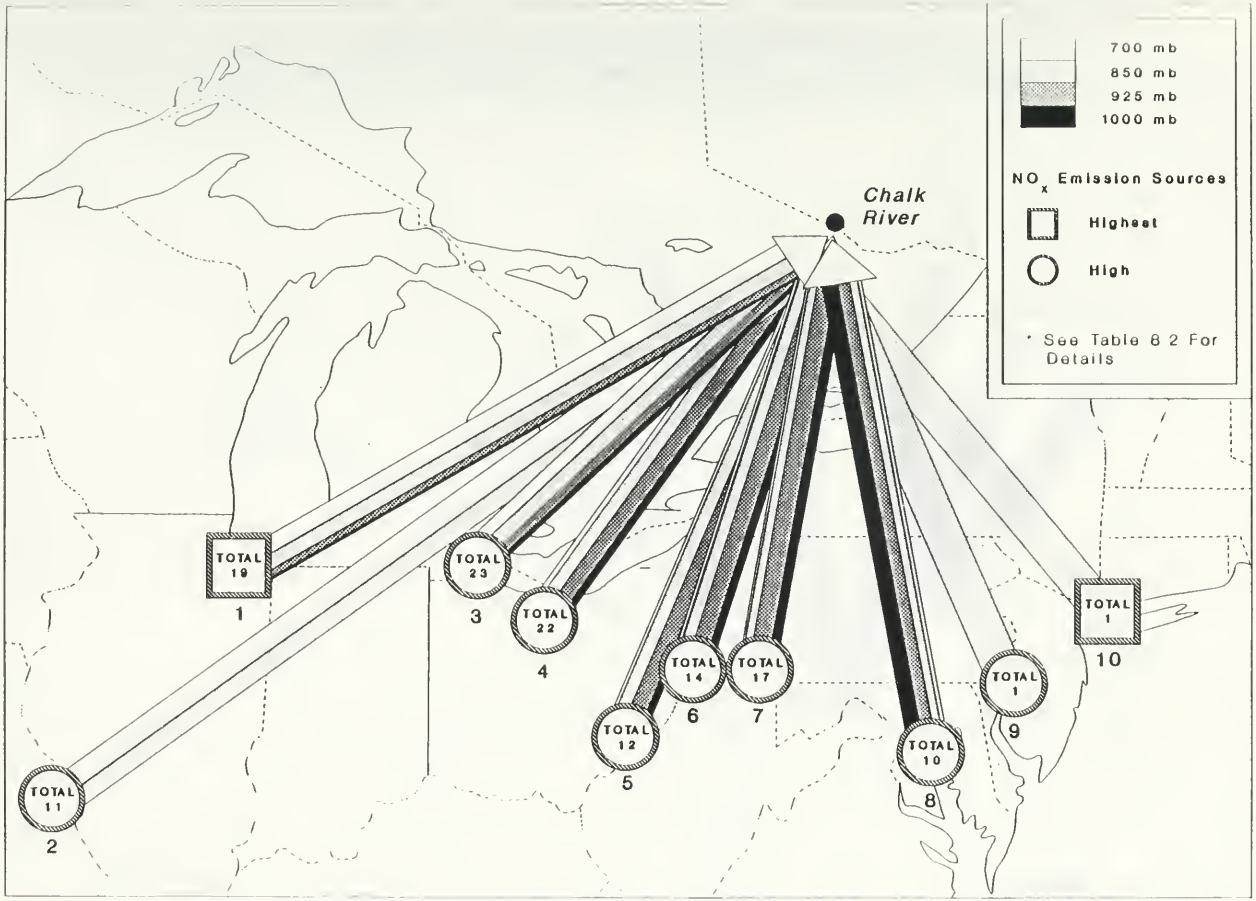


Figure 17.1 NO_3^- WET DEPOSITION EVENTS AT CHALK RIVER - 1985-86

TRANSPORT AT EACH PRESSURE LEVEL

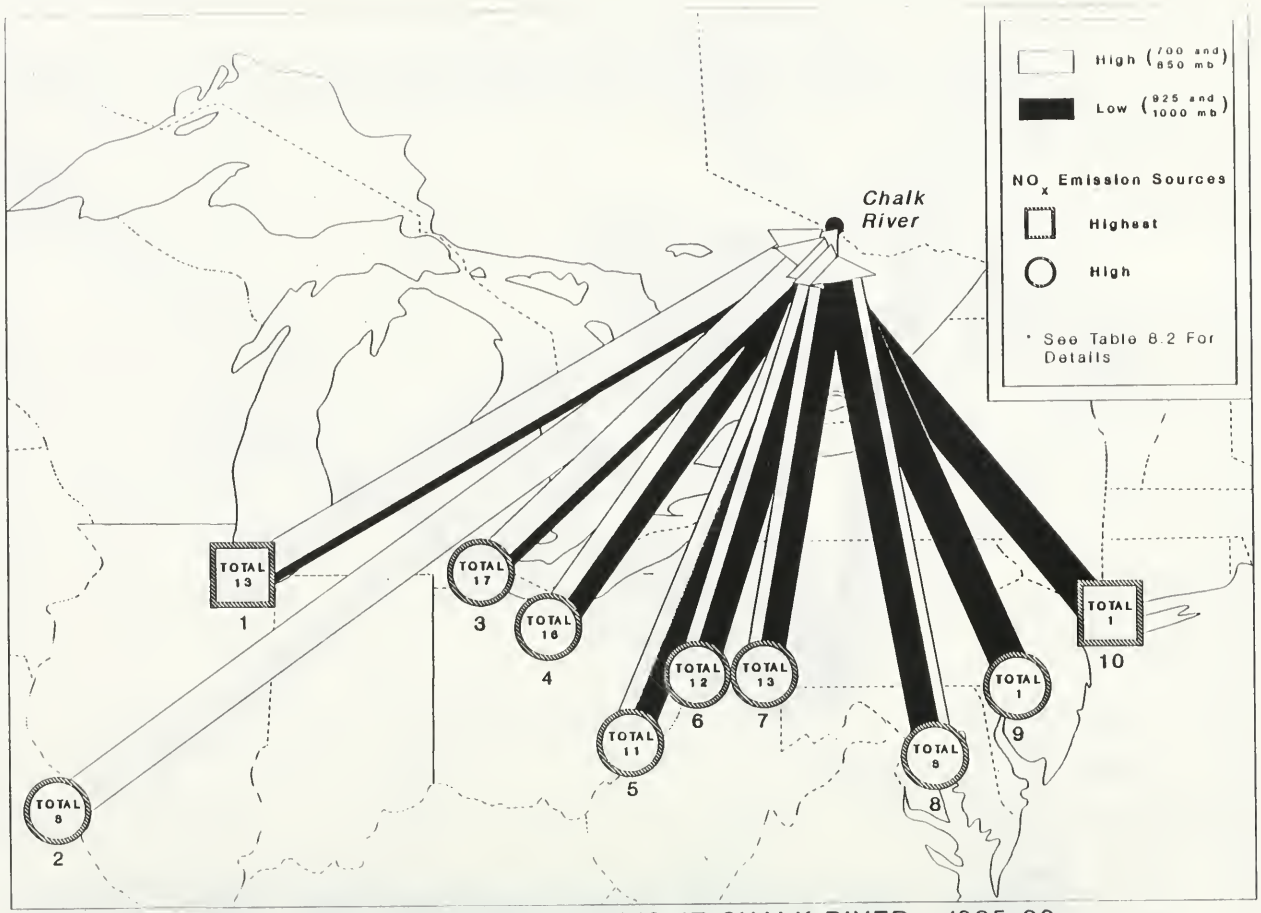


Figure 17.2 NO_3^- WET DEPOSITION EVENTS AT CHALK RIVER - 1985-86

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

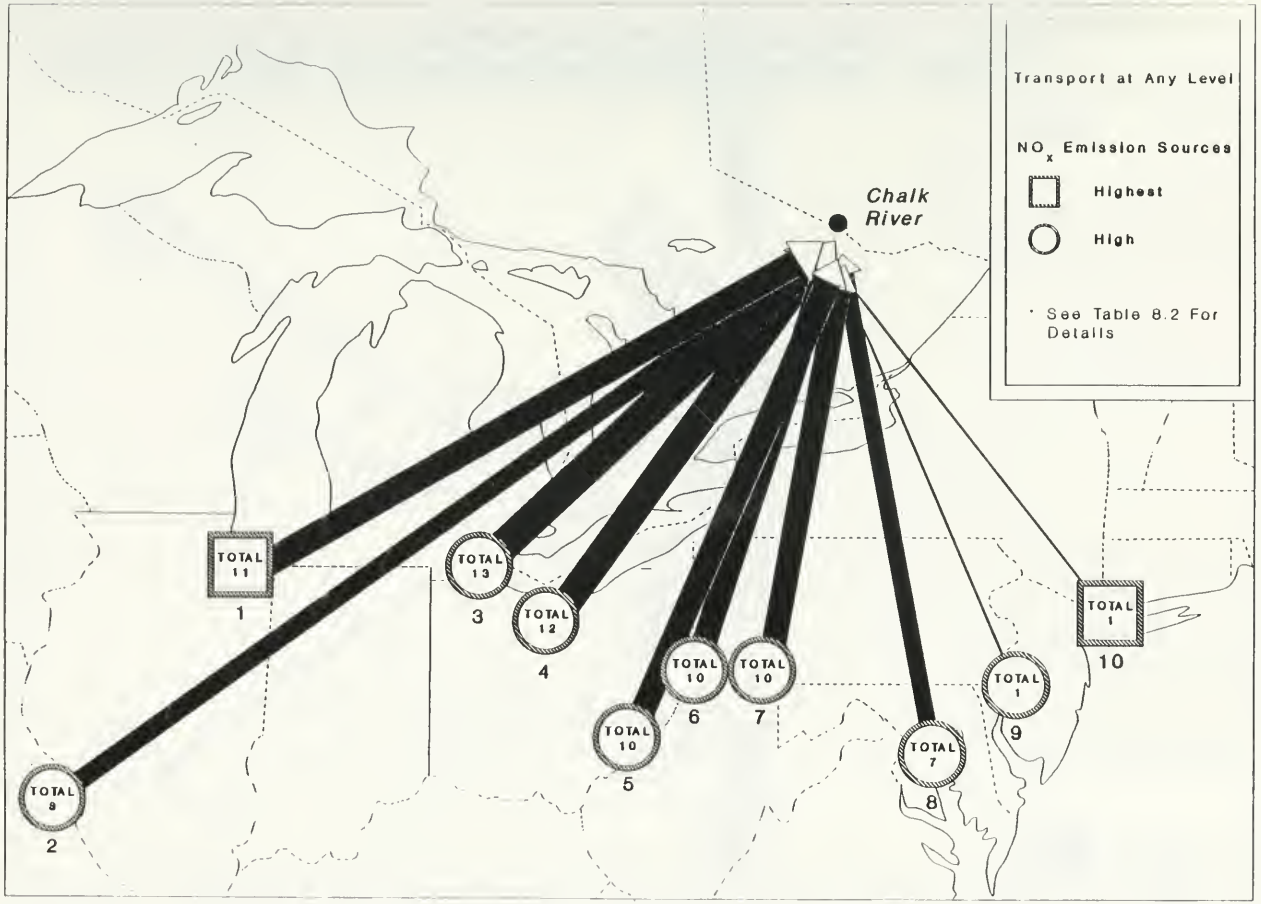


Figure 17.3 NO_3^- WET DEPOSITION EVENTS AT CHALK RIVER - 1985-86

TRANSPORT AT ANY PRESSURE LEVEL

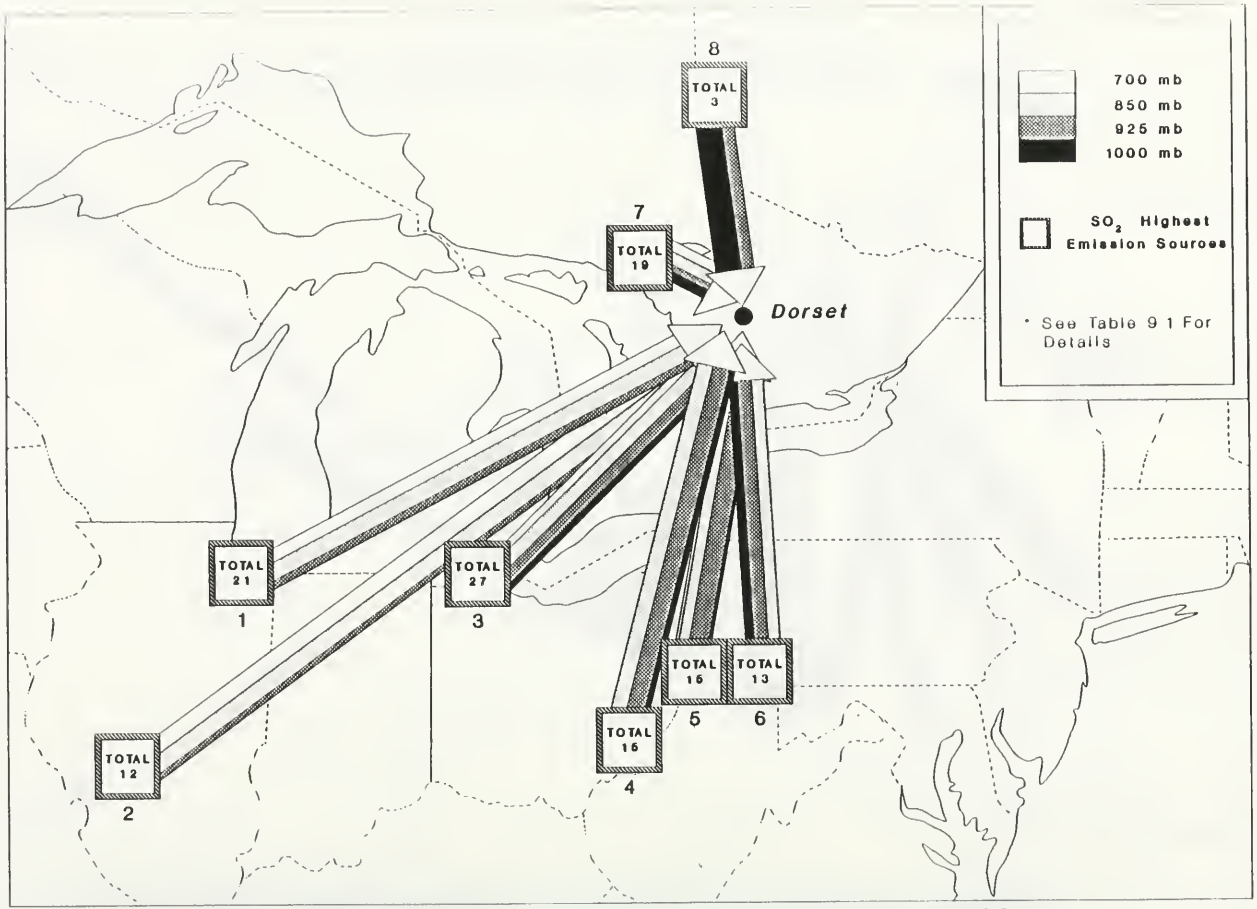


Figure 18.1 SO_4^{--} WET DEPOSITION EVENTS AT DORSET - 1985-86

TRANSPORT AT EACH PRESSURE LEVEL

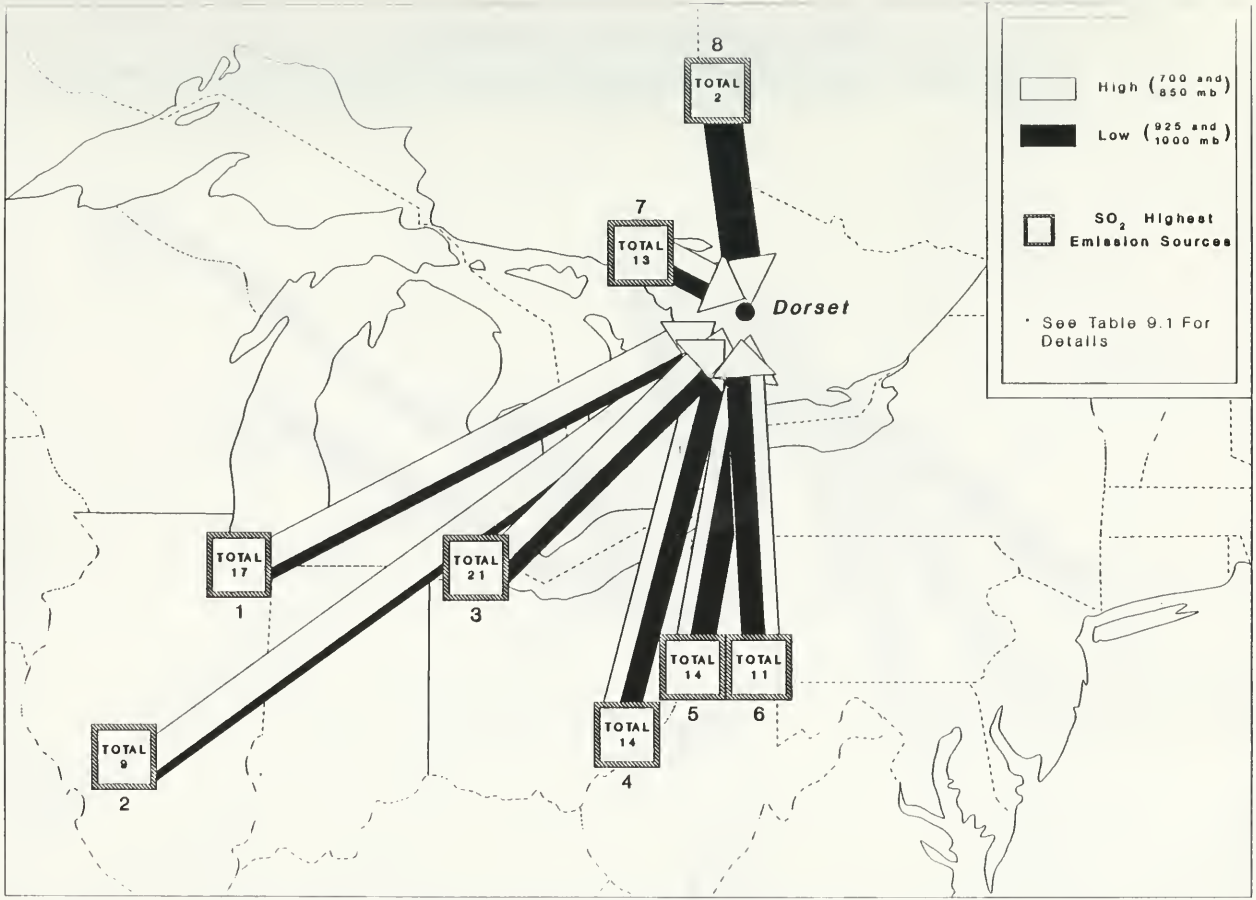


Figure 18.2 SO_4^{--} WET DEPOSITION EVENTS AT DORSET - 1985-86

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

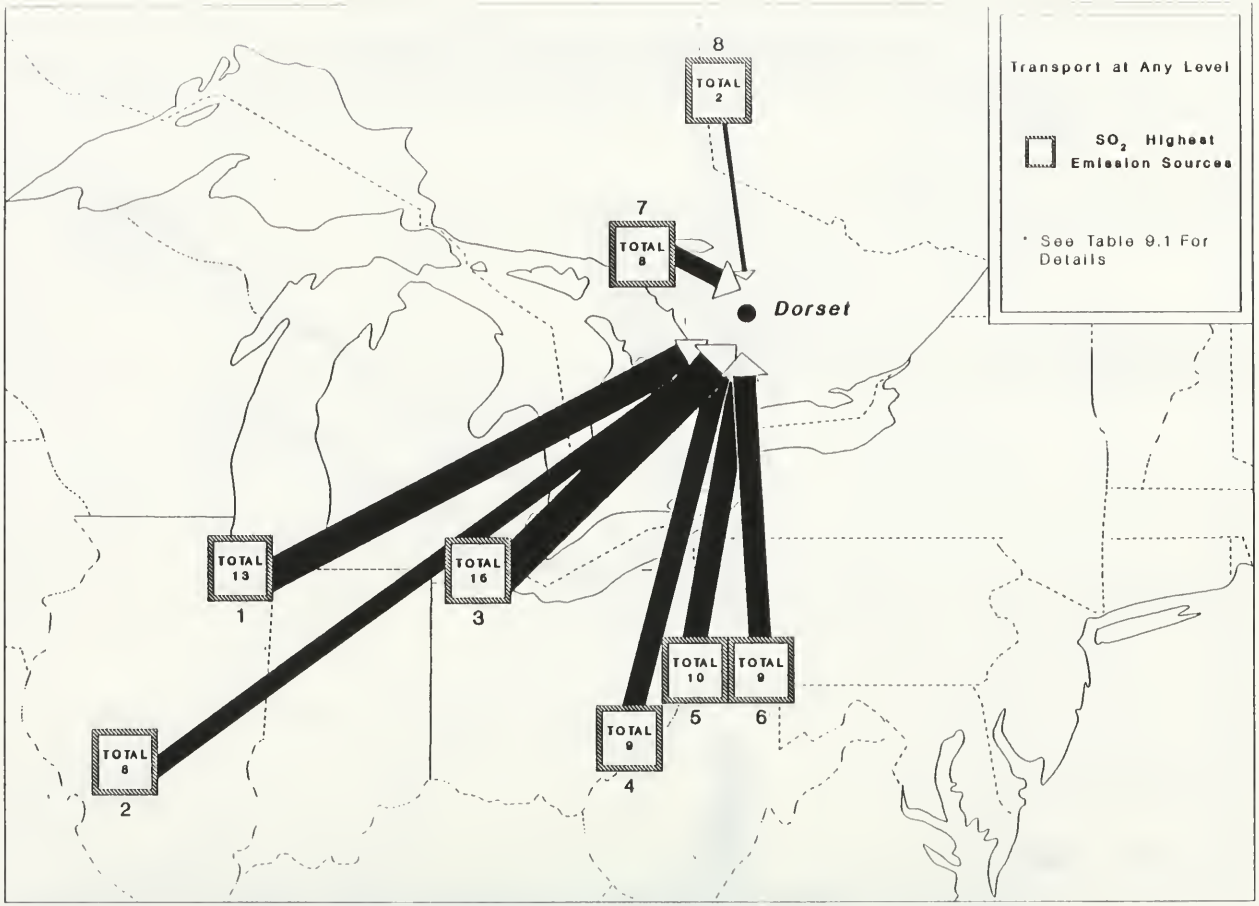


Figure 18.3 SO_4^{--} WET DEPOSITION EVENTS AT DORSET - 1985-86

TRANSPORT AT ANY PRESSURE LEVEL

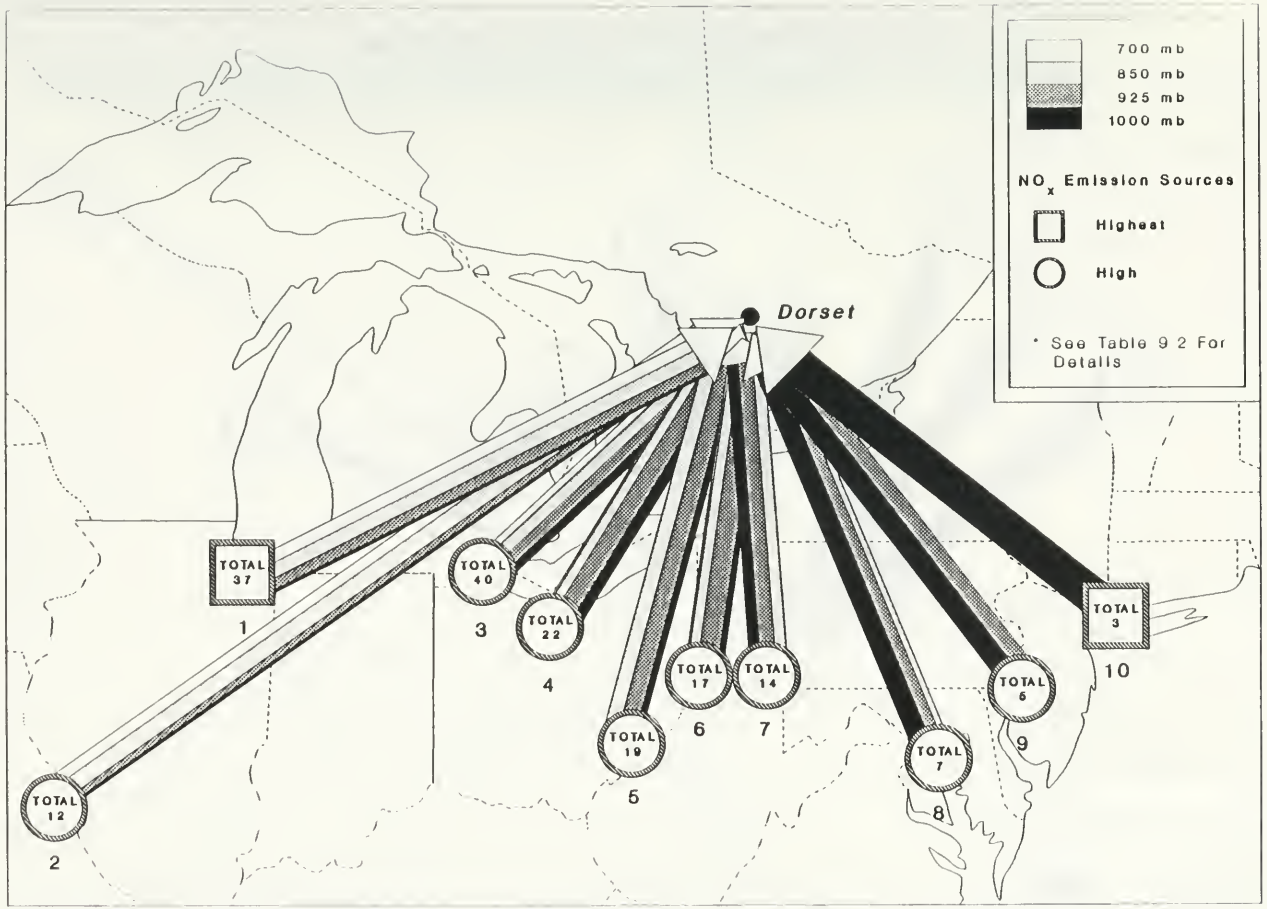


Figure 19.1 NO_3^- WET DEPOSITION EVENTS AT DORSET - 1985-86

TRANSPORT AT EACH PRESSURE LEVEL

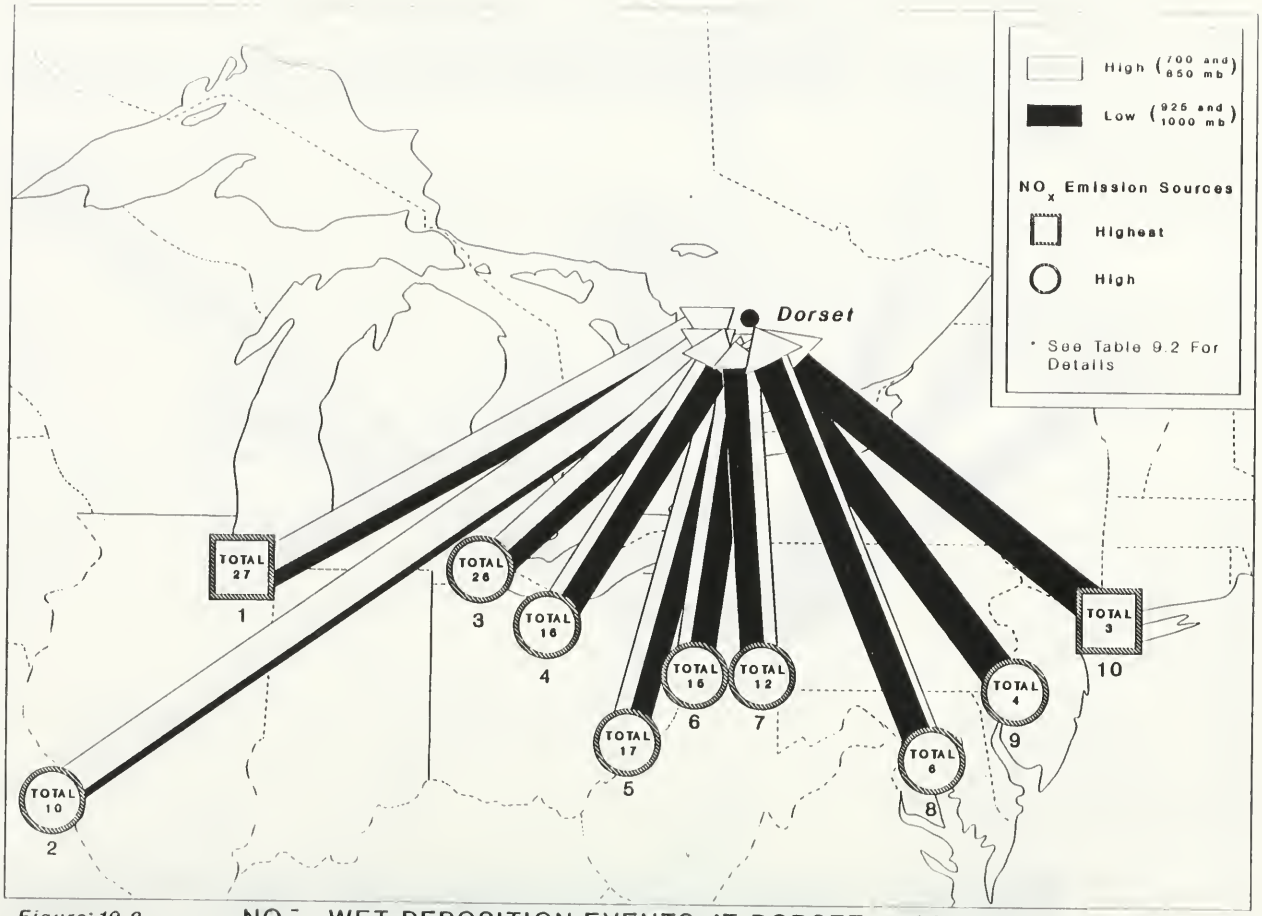


Figure 19.2 NO_3^- WET DEPOSITION EVENTS AT DORSET - 1985-86

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

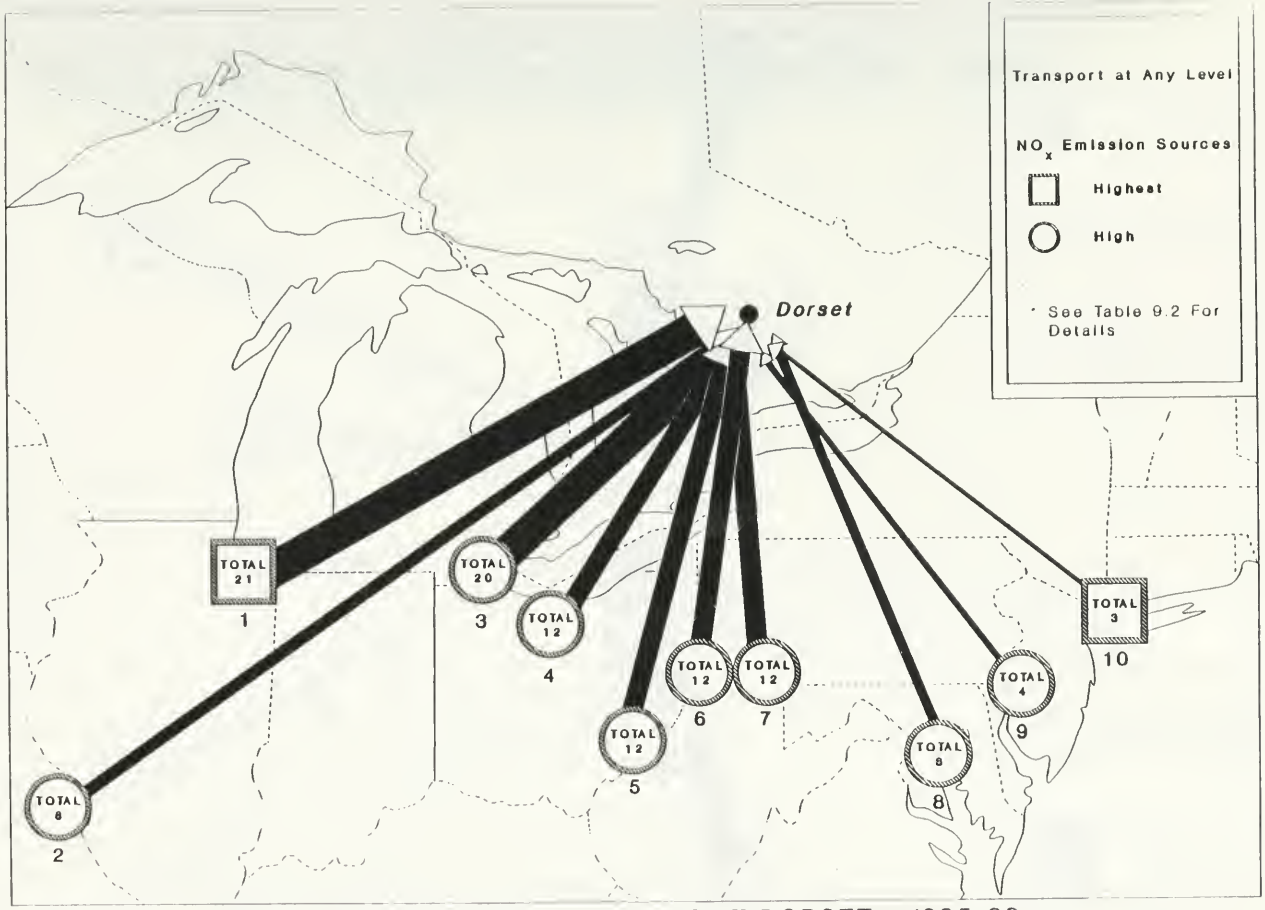


Figure 19.3 NO_3^- WET DEPOSITION EVENTS AT DORSET - 1985-86

TRANSPORT AT ANY PRESSURE LEVEL

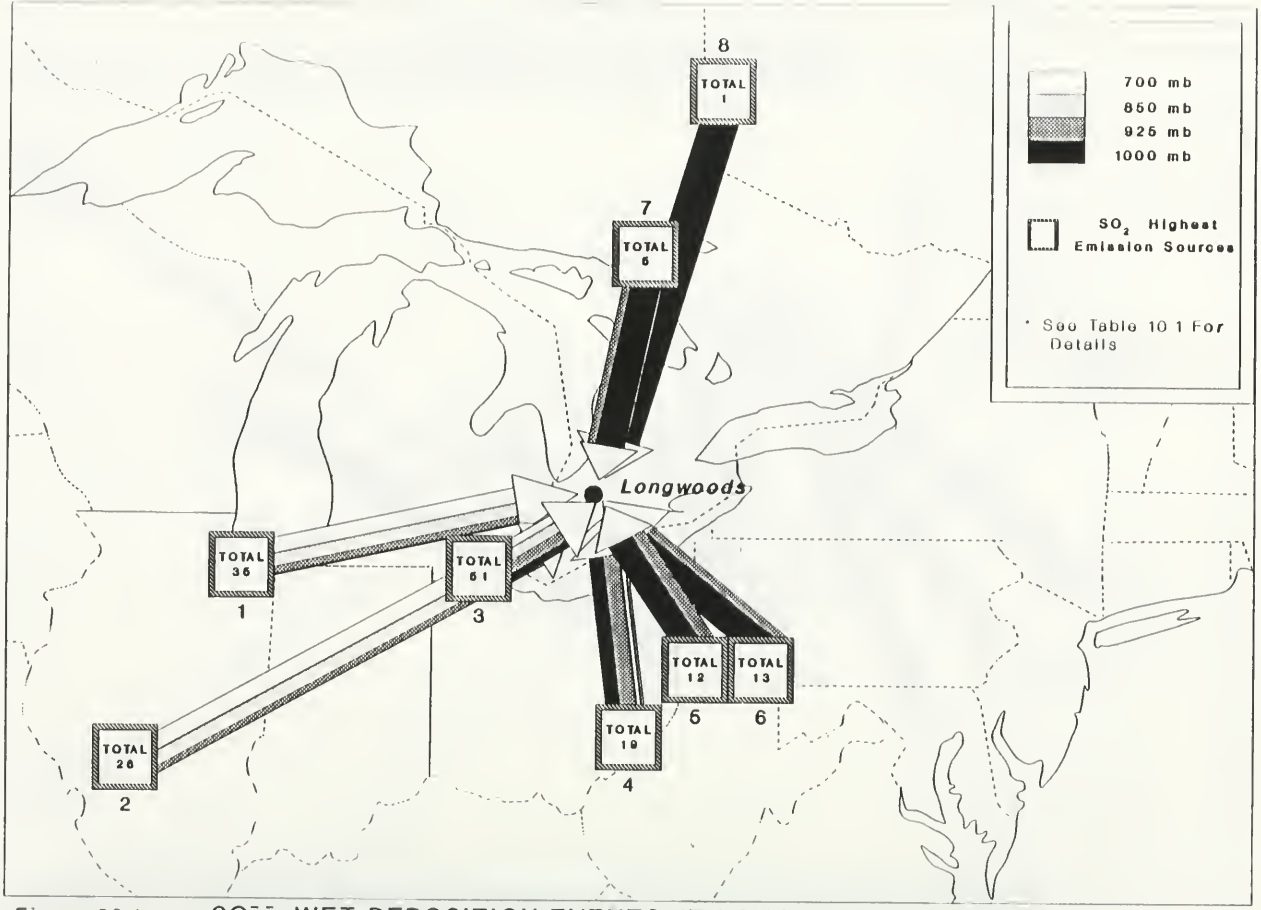


Figure 20.1 SO_4^{--} WET DEPOSITION EVENTS AT LONGWOODS - 1985-86

TRANSPORT AT EACH PRESSURE LEVEL

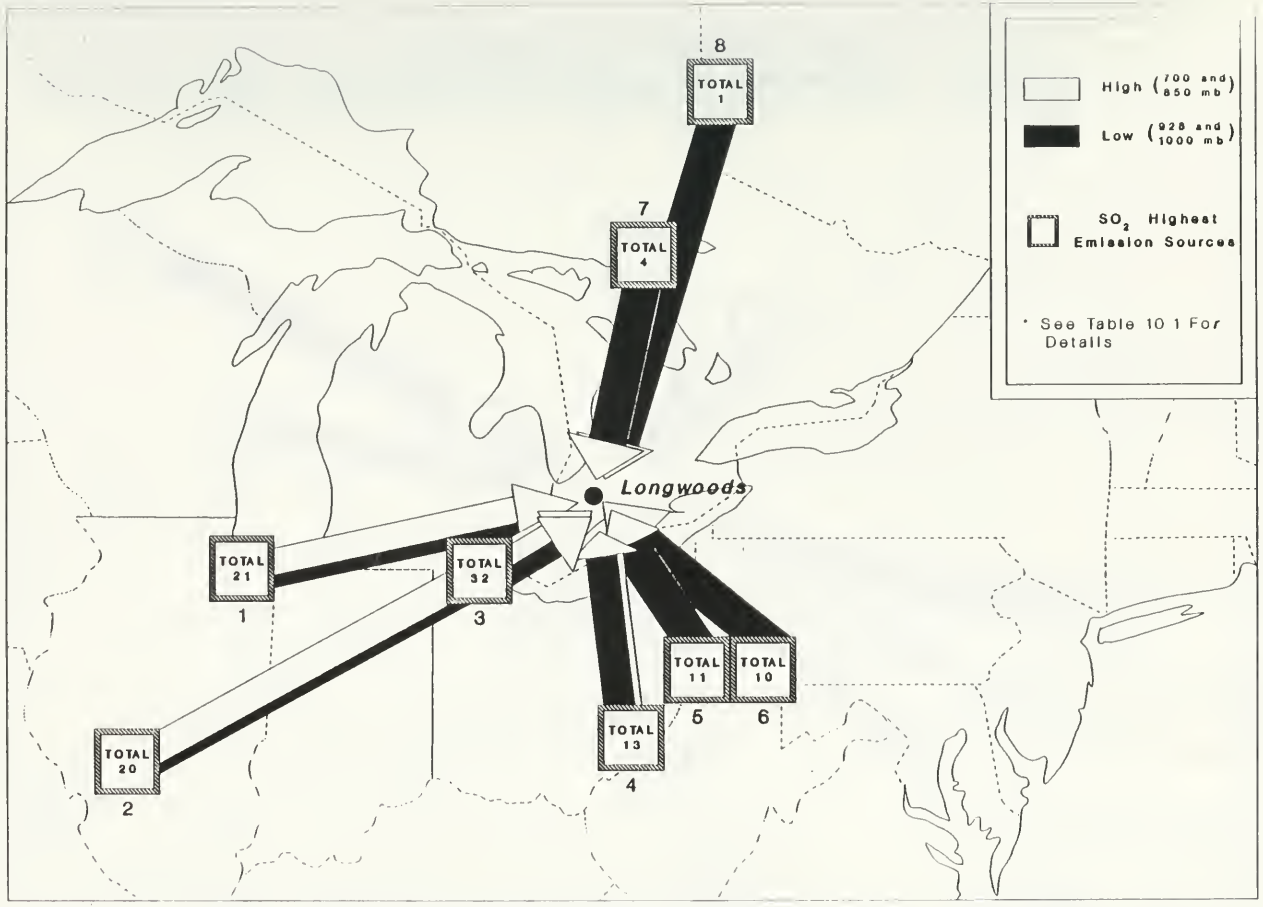


Figure 20.2 SO_4^{--} WET DEPOSITION EVENTS AT LONGWOODS - 1985-86

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

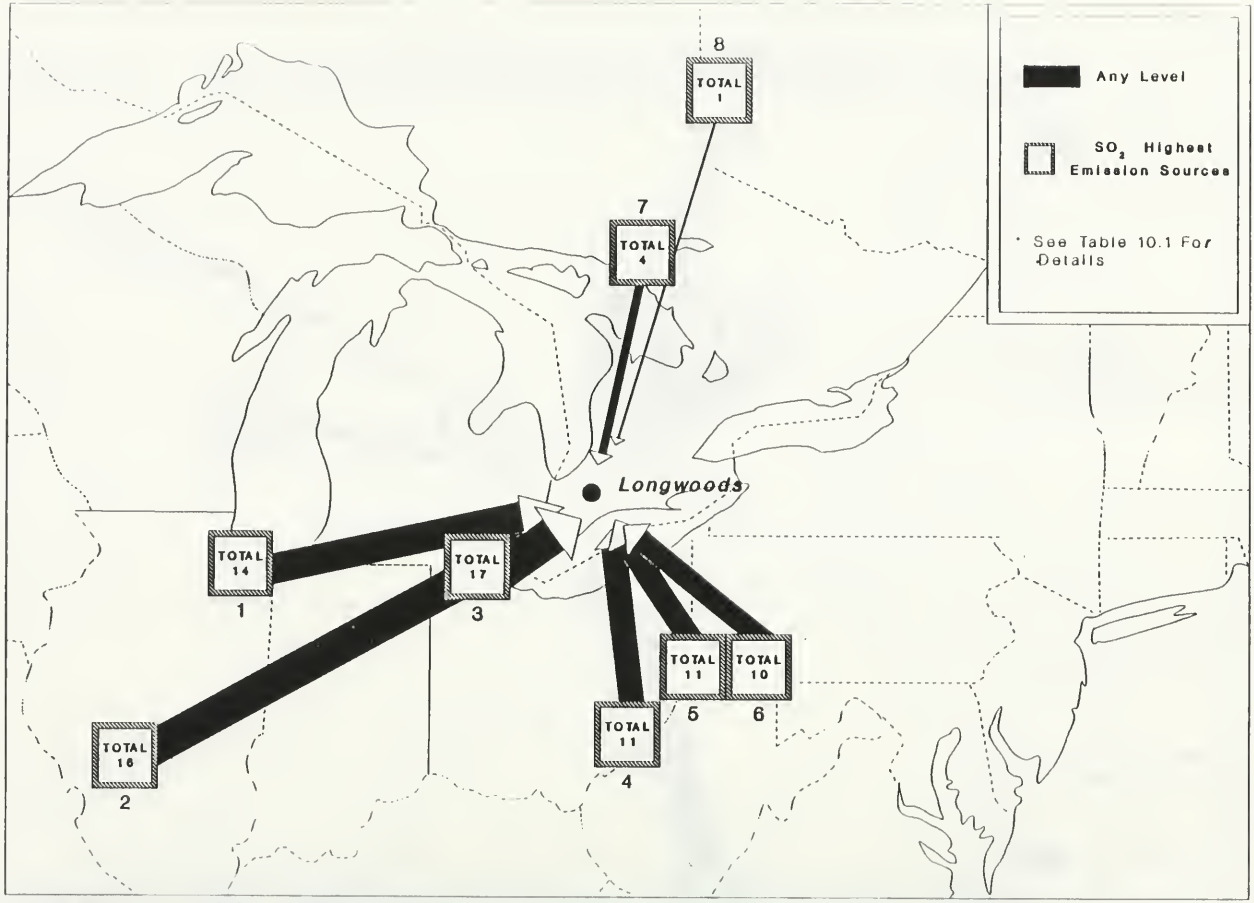


Figure 20.3 SO_4^{--} WET DEPOSITION EVENTS AT LONGWOODS - 1985-86

TRANSPORT AT ANY PRESSURE LEVEL

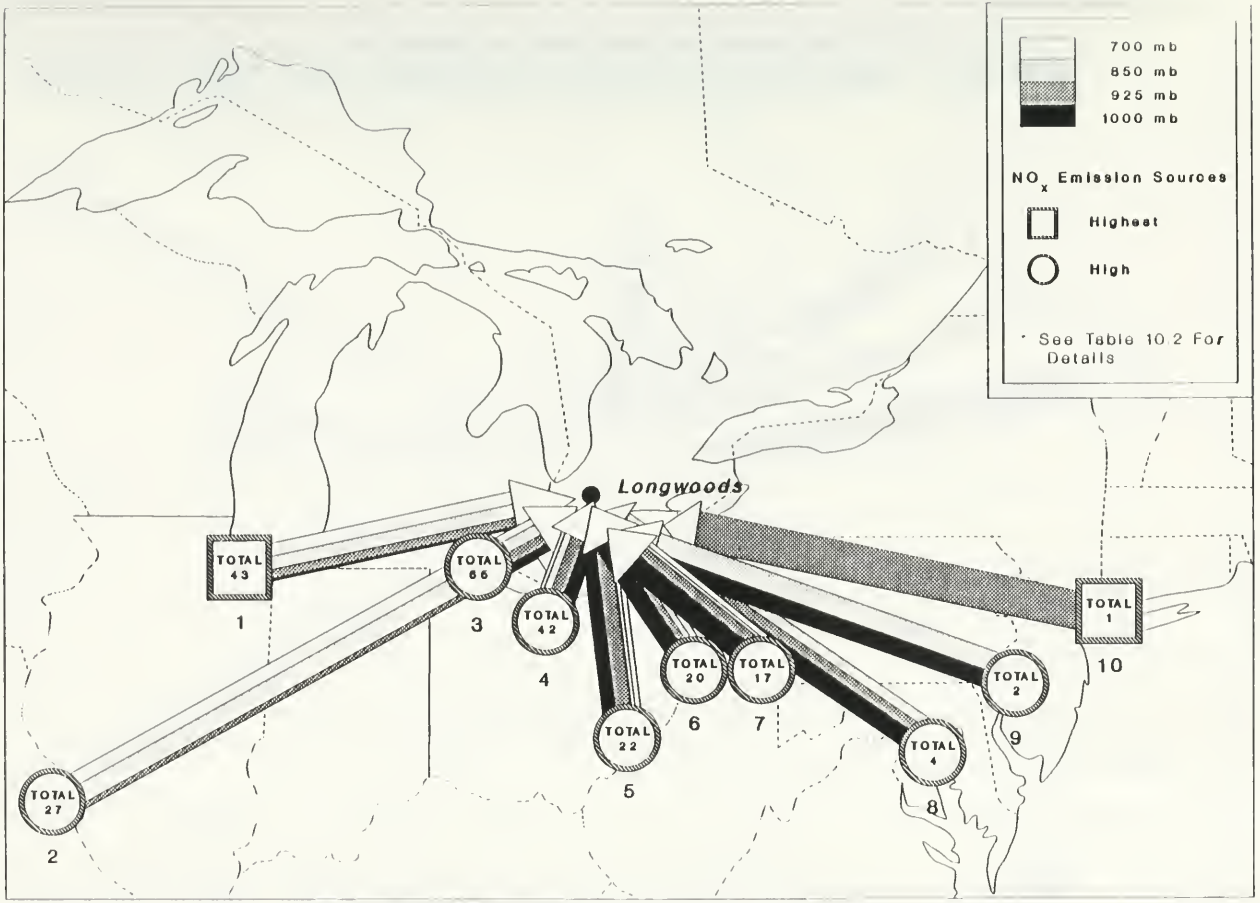


Figure 21.1 NO_3^- WET DEPOSITION EVENTS AT LONGWOODS - 1985-86

TRANSPORT AT EACH PRESSURE LEVEL

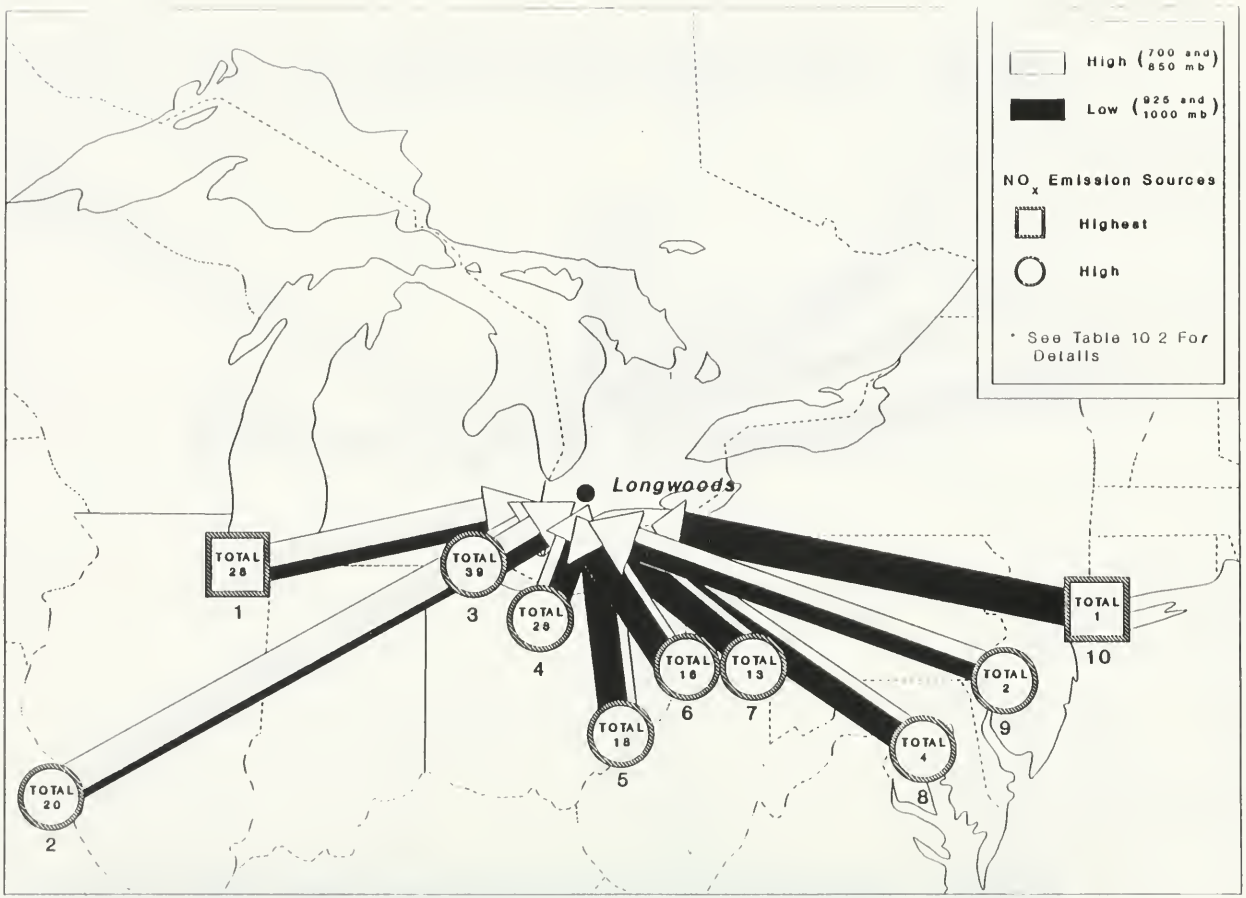


Figure 21.2 NO_3^- WET DEPOSITION EVENTS AT LONGWOODS - 1985-86

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

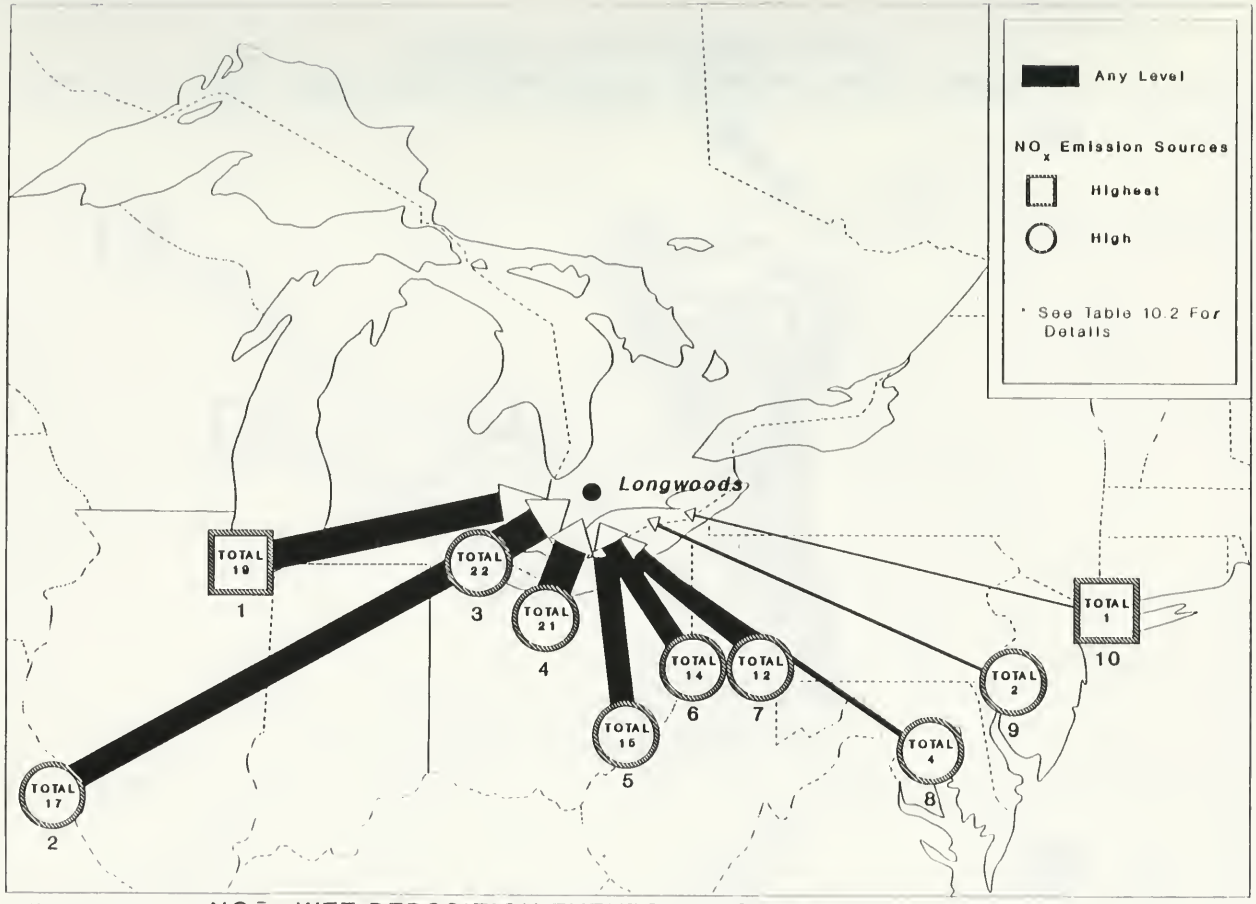


Figure 21.3 NO_3^- WET DEPOSITION EVENTS AT LONGWOODS - 1985-86

TRANSPORT AT ANY PRESSURE LEVEL

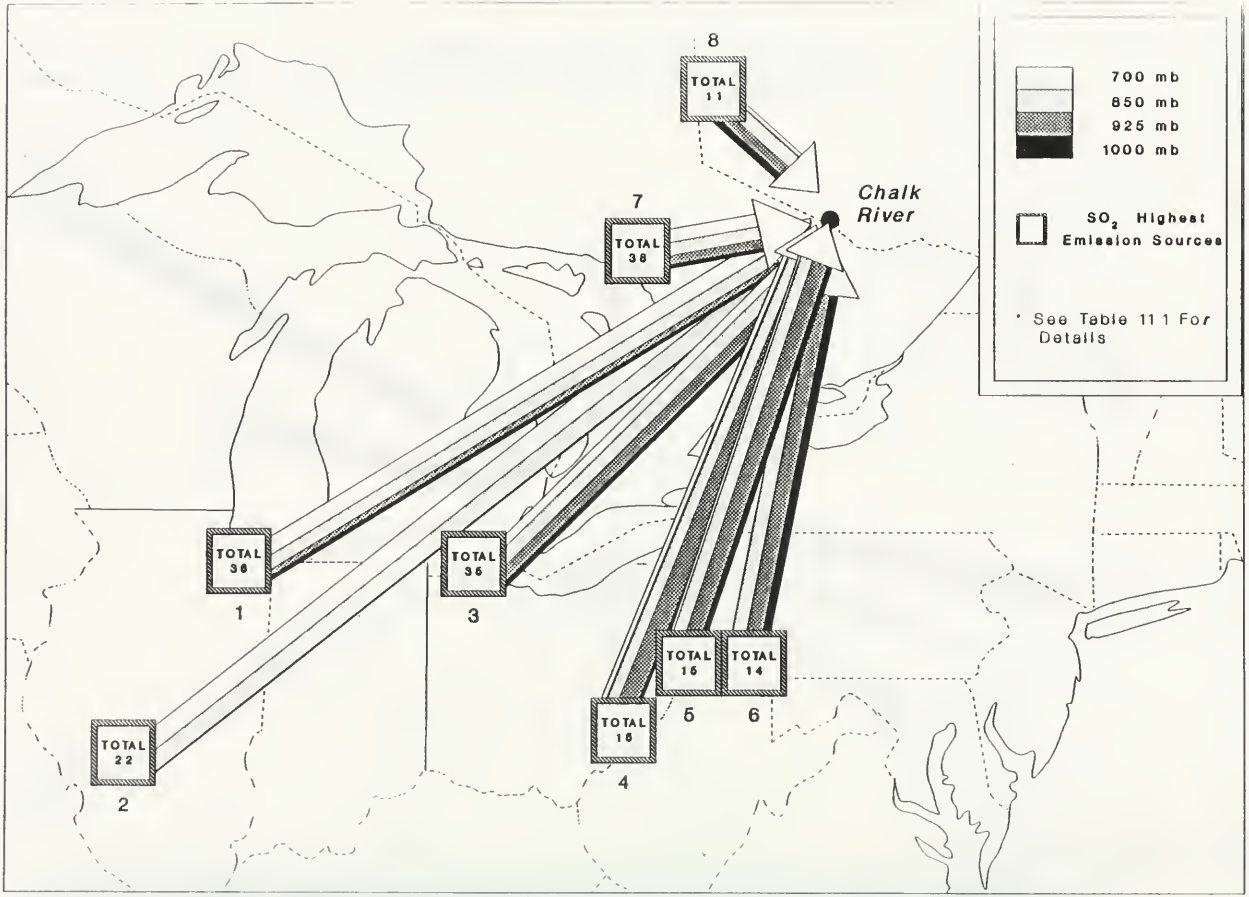


Figure 22.1 SO_4^{--} WET DEPOSITION EVENTS AT CHALK RIVER - 1985-88

TRANSPORT AT EACH PRESSURE LEVEL

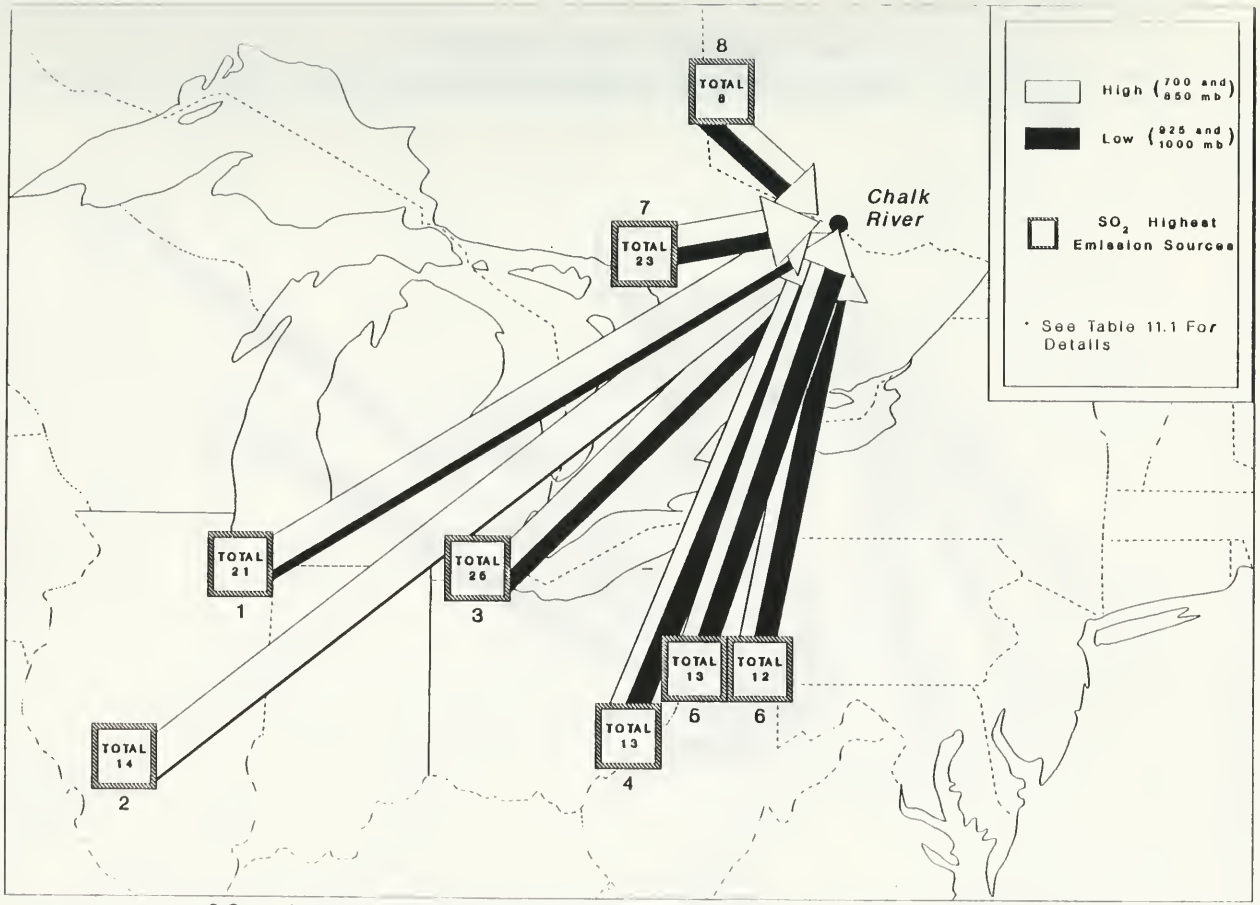


Figure 22.2 SO_4^{--} WET DEPOSITION EVENTS AT CHALK RIVER - 1985-88

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

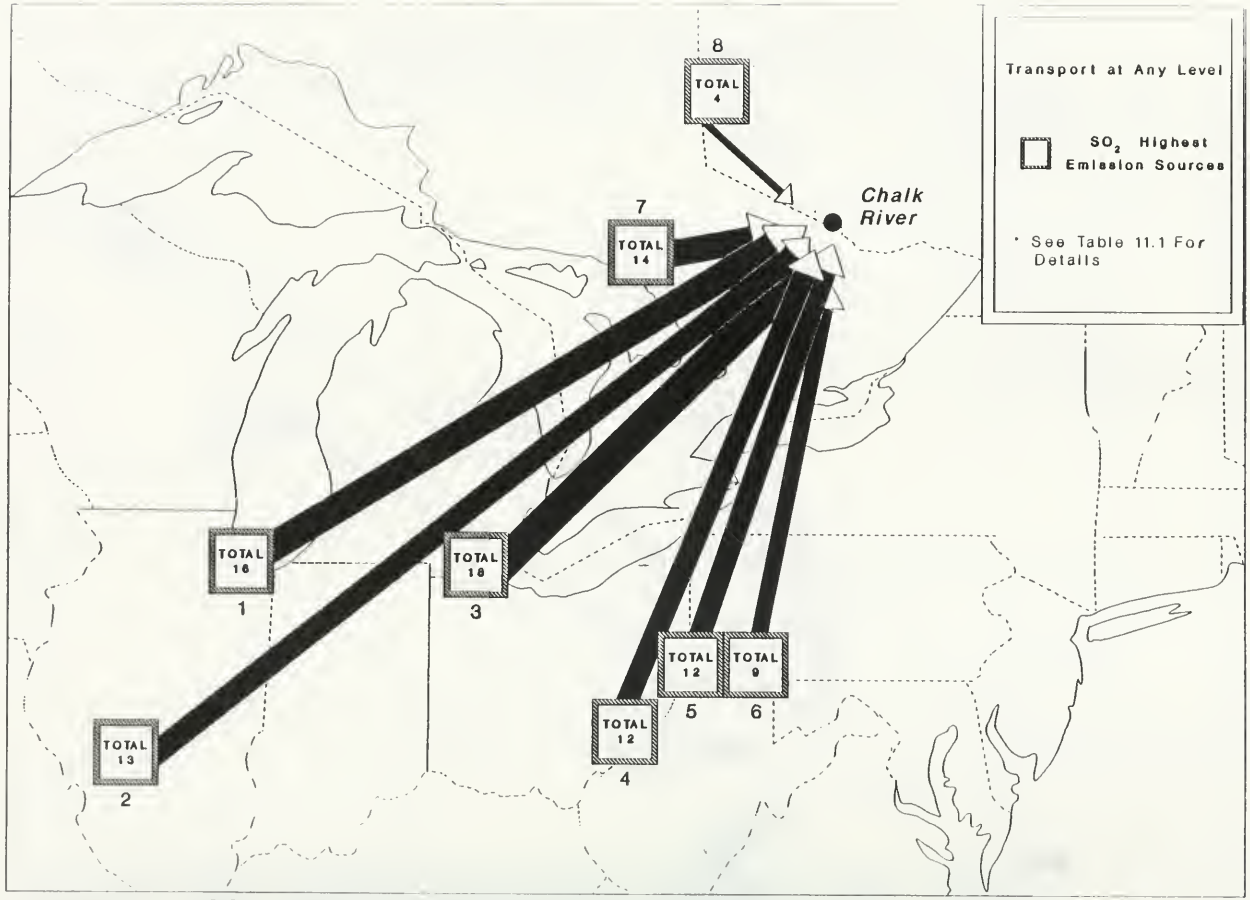


Figure 22.3 SO_4^{--} WET DEPOSITION EVENTS AT CHALK RIVER - 1985-88

TRANSPORT AT ANY PRESSURE LEVEL

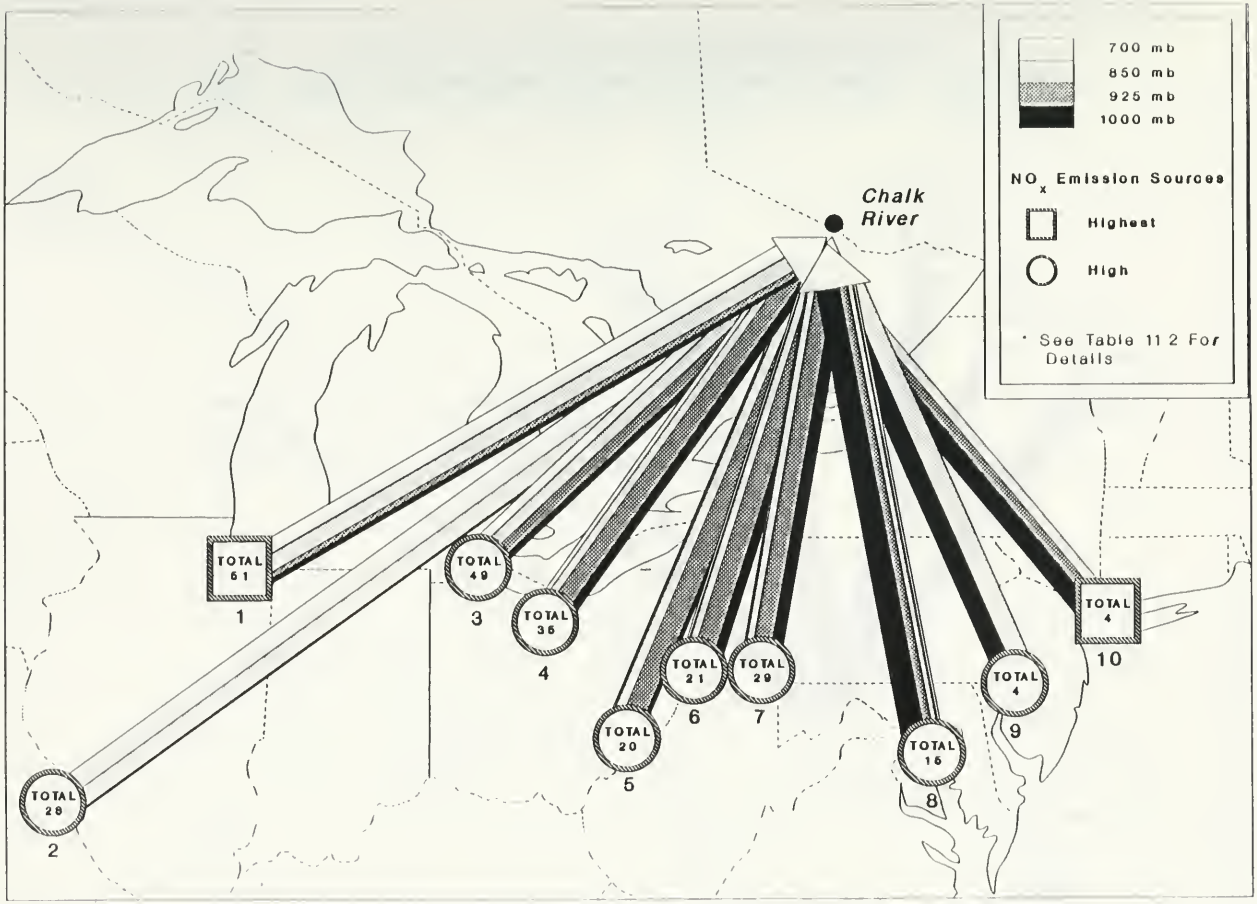


Figure 23.1 NO_3^- WET DEPOSITION EVENTS AT CHALK RIVER - 1985-88

TRANSPORT AT EACH PRESSURE LEVEL

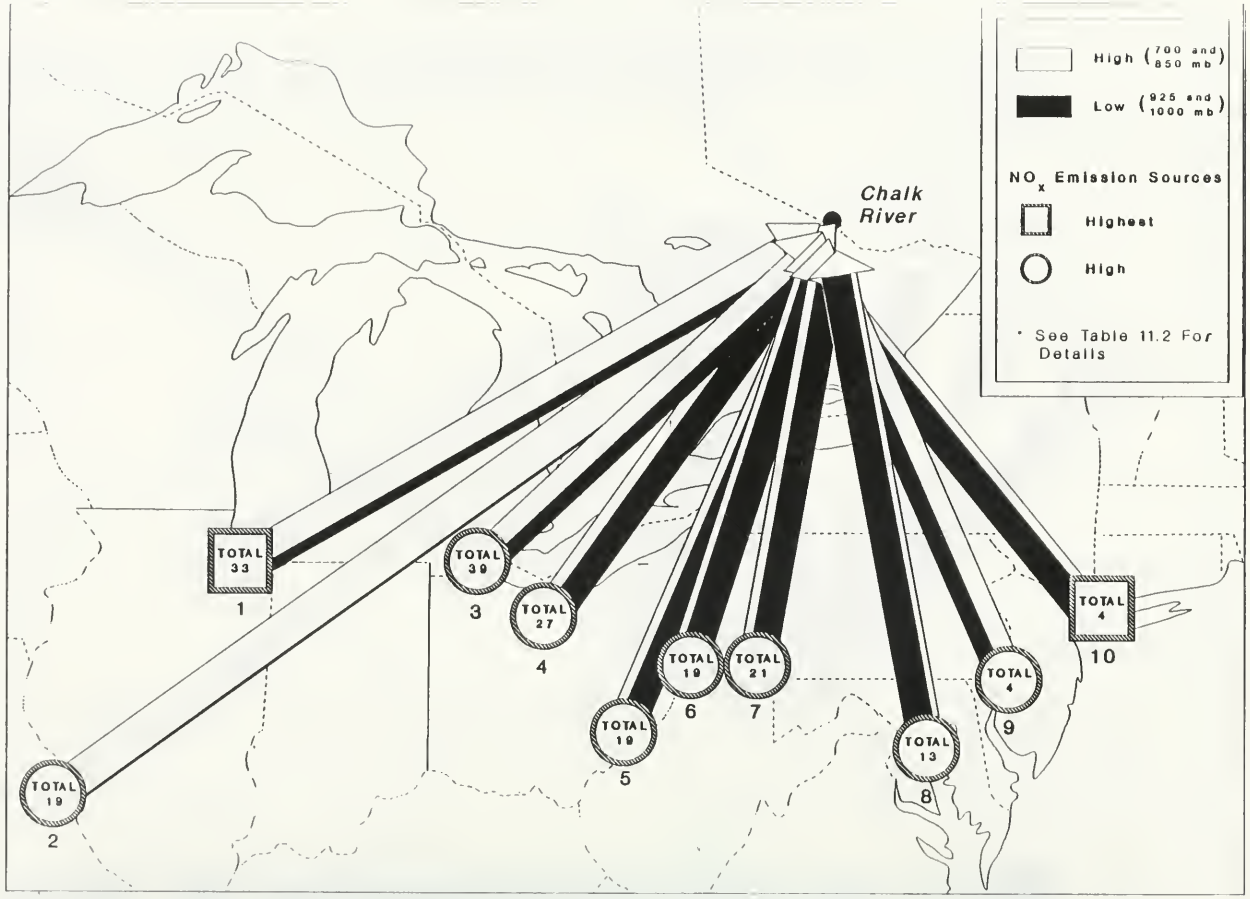


Figure 23.2 NO_3^- WET DEPOSITION EVENTS AT CHALK RIVER - 1985-88

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

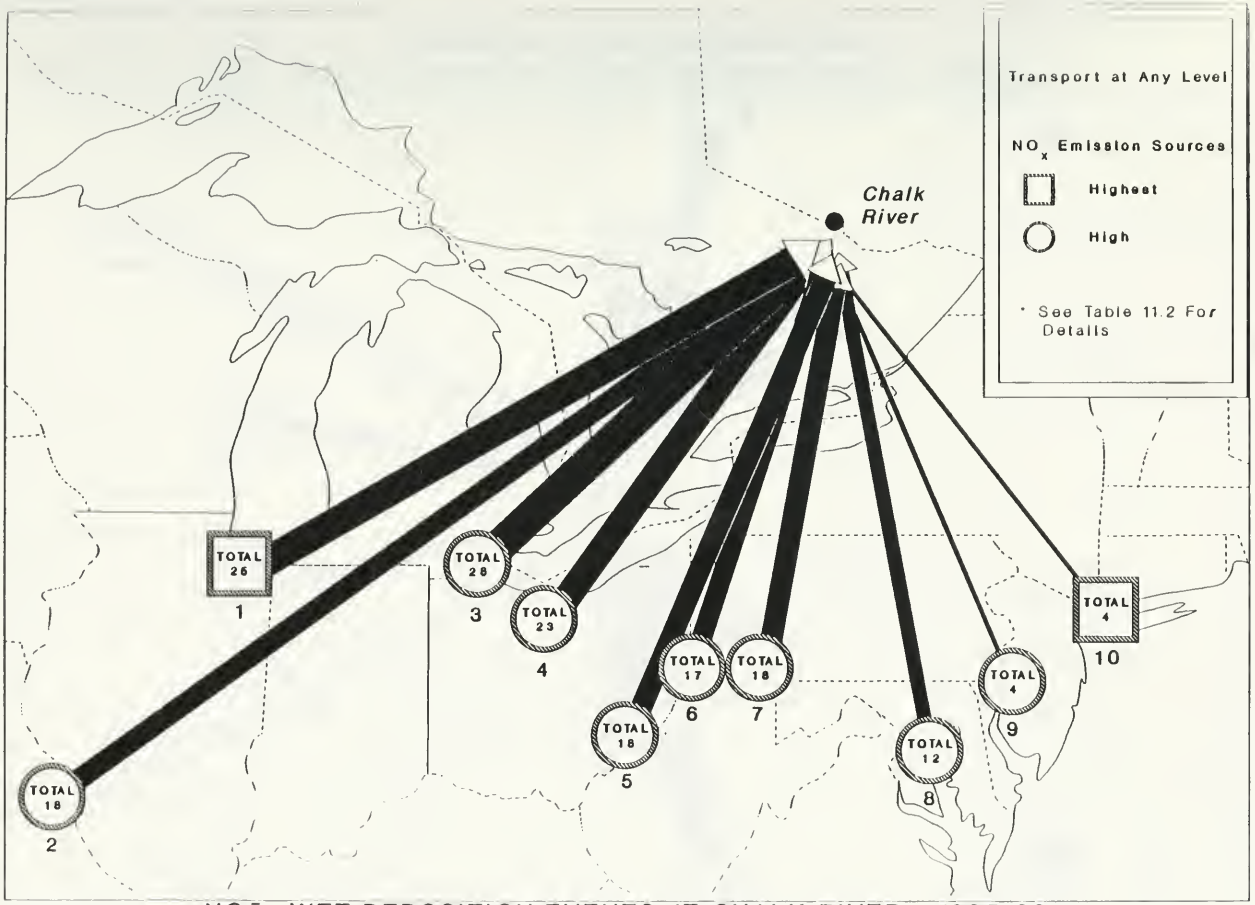


Figure 23.3 NO_3^- WET DEPOSITION EVENTS AT CHALK RIVER - 1985-88

TRANSPORT AT ANY PRESSURE LEVEL

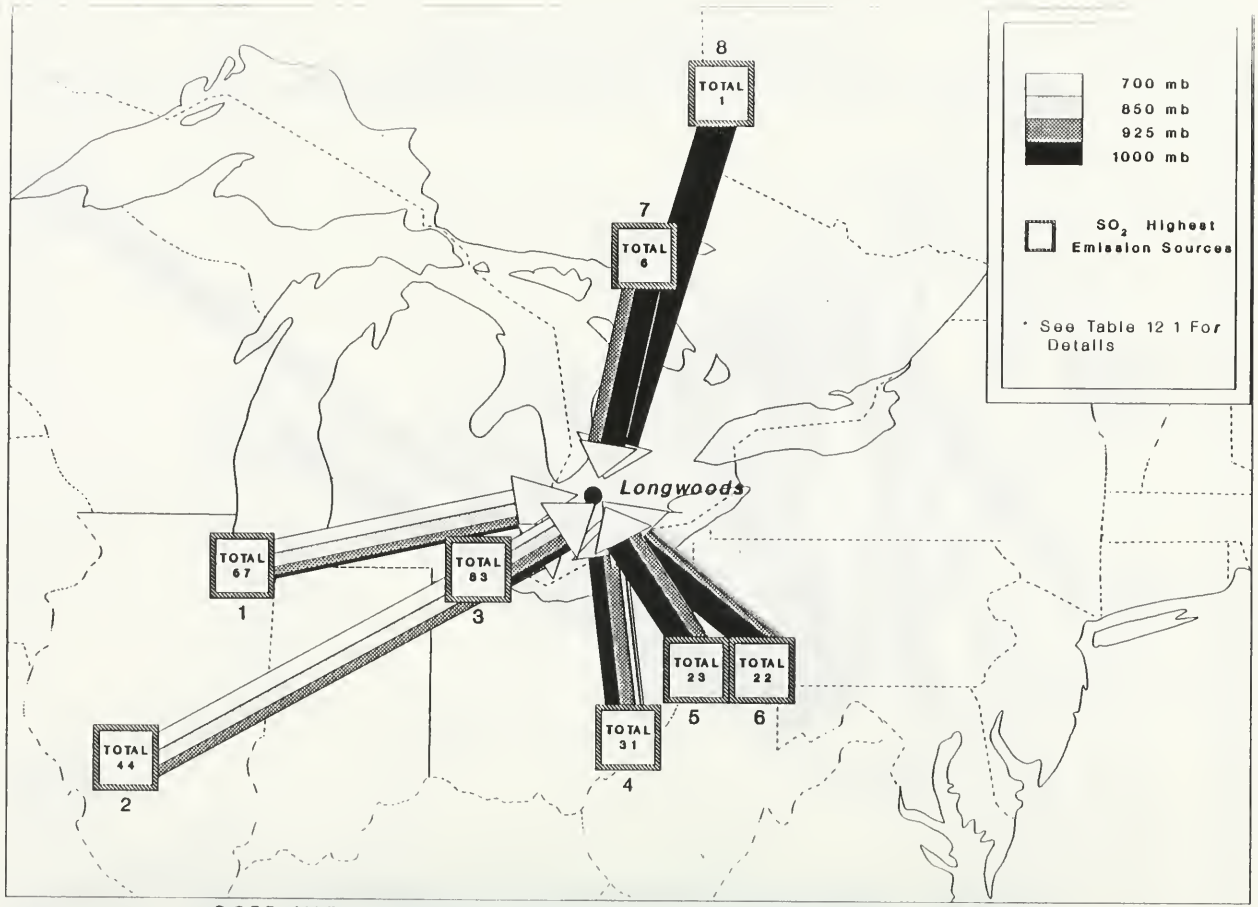


Figure 24.1 SO_4^{--} WET DEPOSITION EVENTS AT LONGWOODS - 1985-88

TRANSPORT AT EACH PRESSURE LEVEL

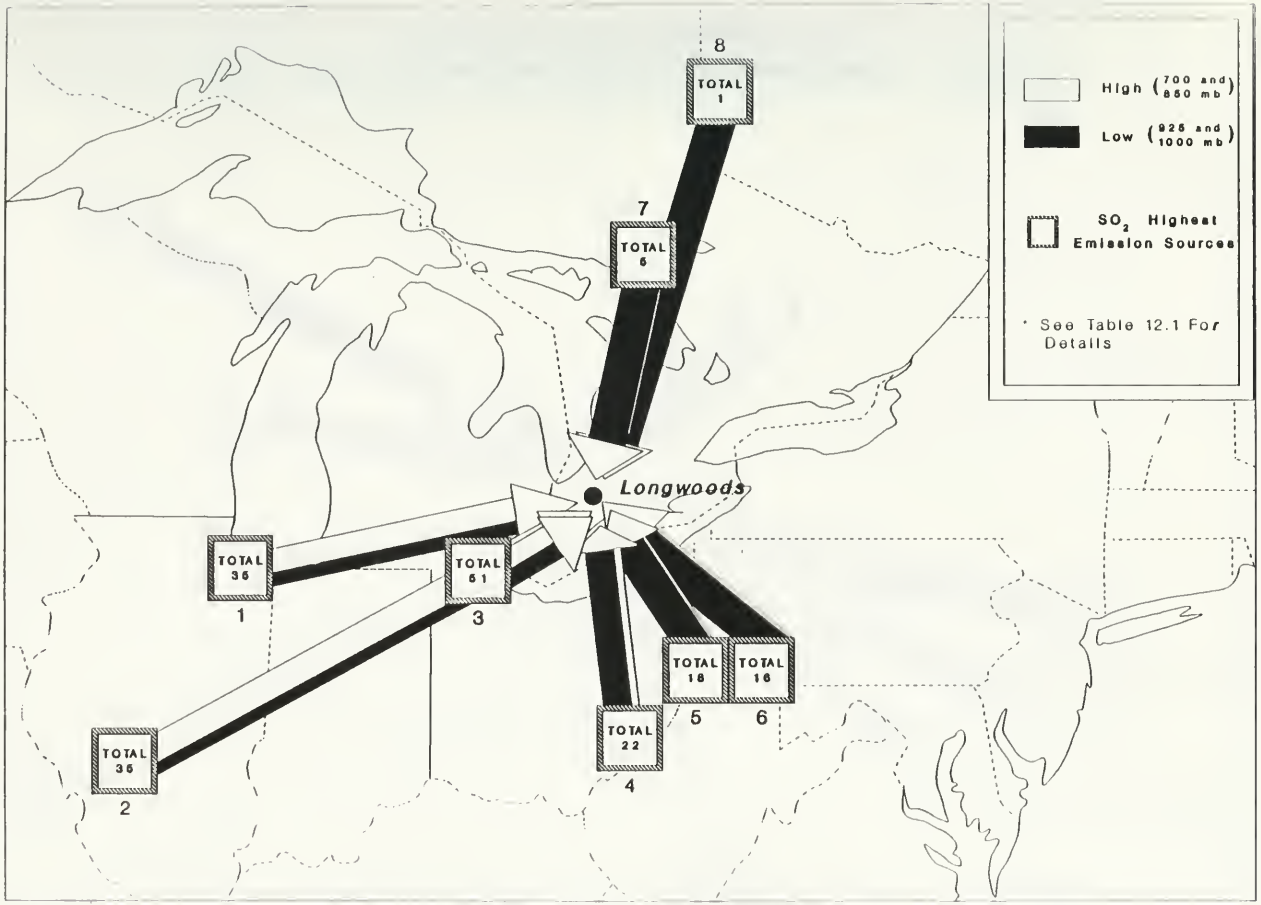


Figure 24.2 SO_4^{--} WET DEPOSITION EVENTS AT LONGWOODS - 1985-88

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

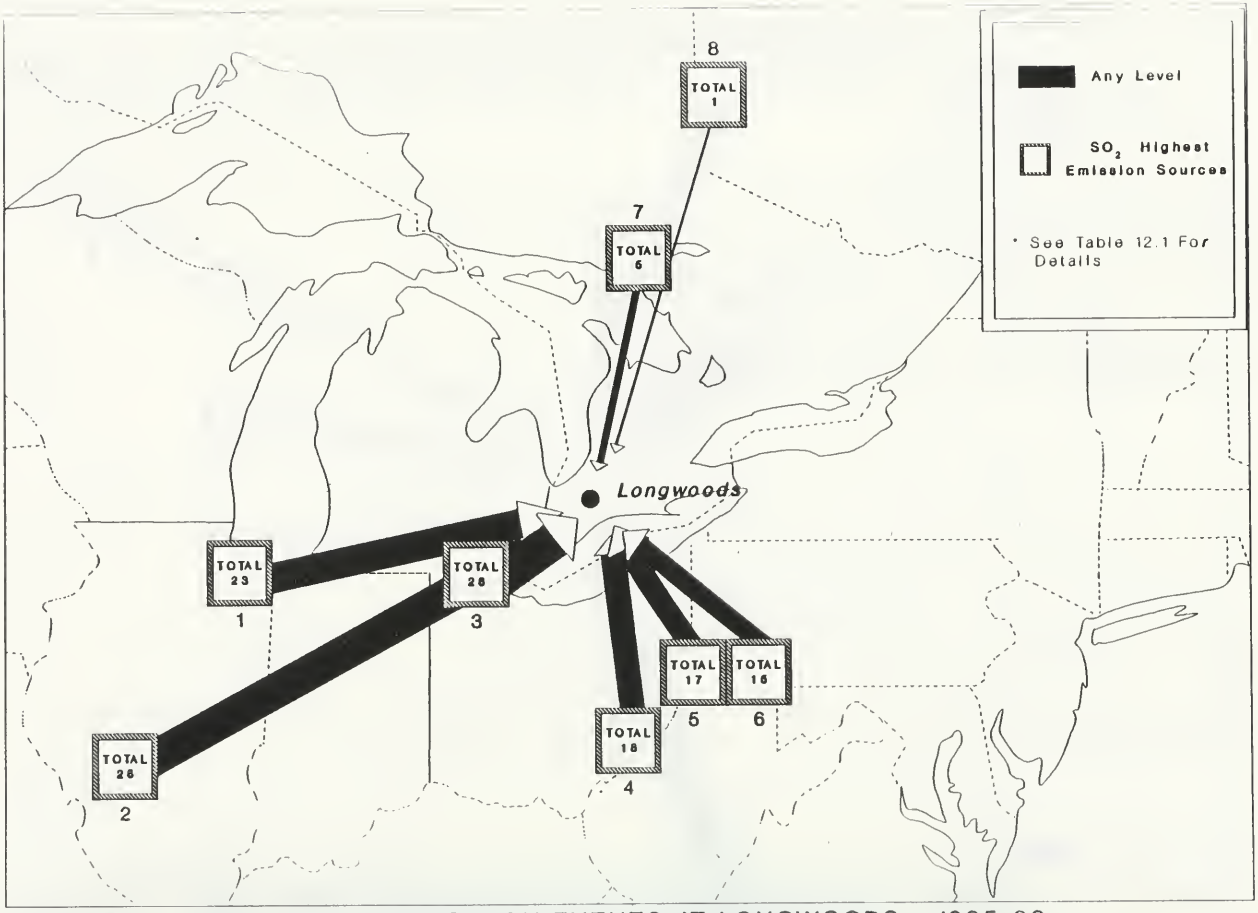


Figure 24.3 SO_4^{--} WET DEPOSITION EVENTS AT LONGWOODS - 1985-88

TRANSPORT AT ANY PRESSURE LEVEL

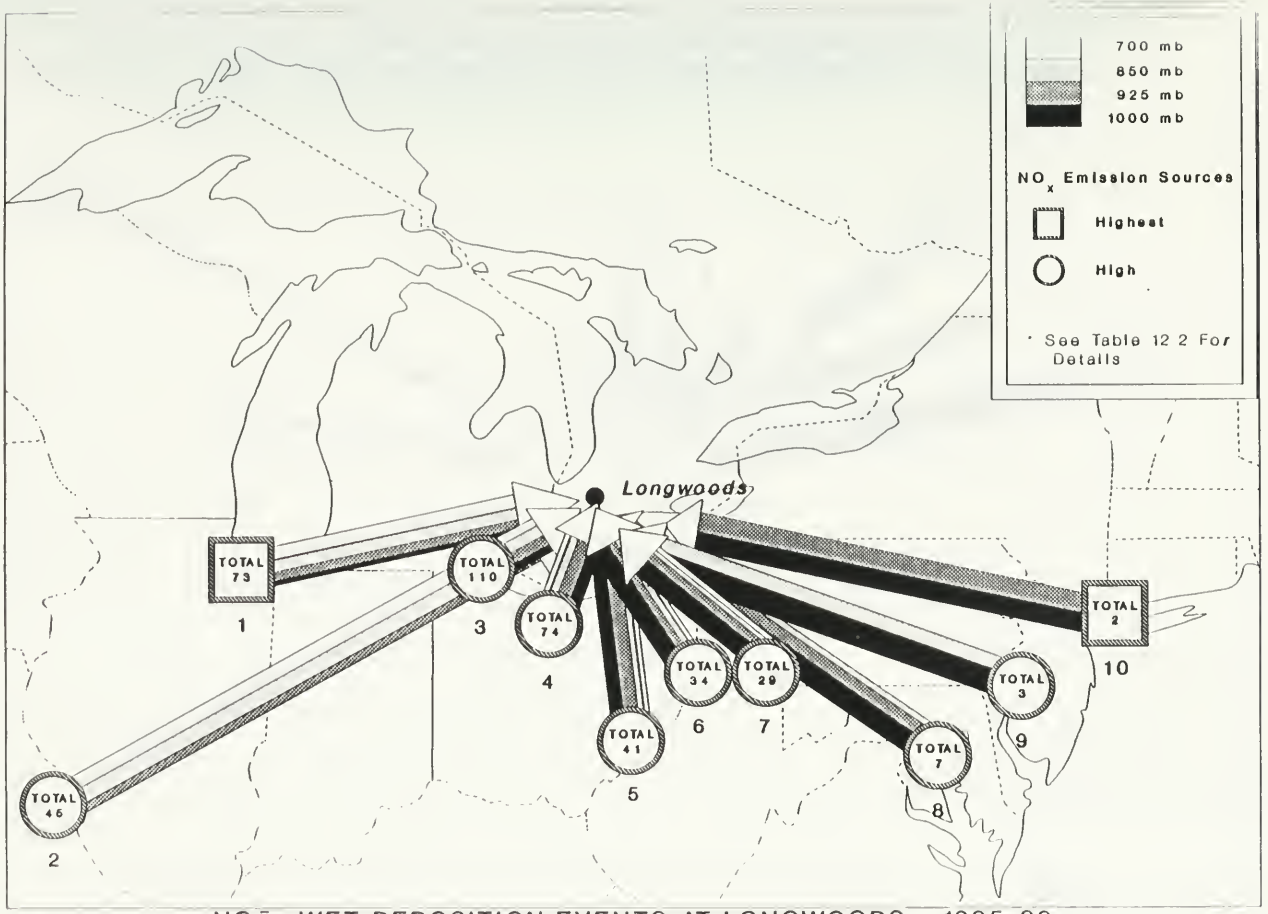


Figure 25.1 NO_3^- WET DEPOSITION EVENTS AT LONGWOODS - 1985-88

TRANSPORT AT EACH PRESSURE LEVEL

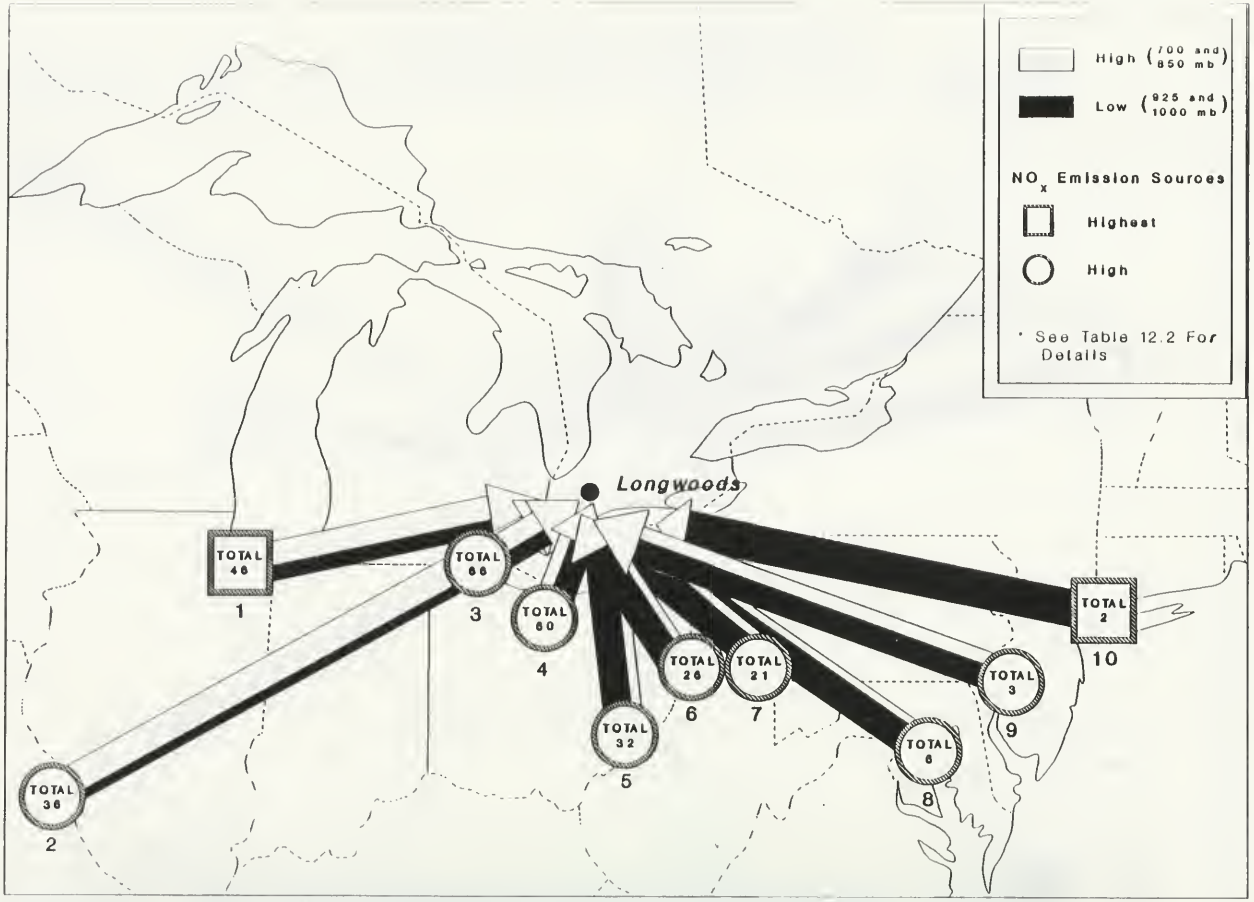


Figure 25.2 NO_3^- WET DEPOSITION EVENTS AT LONGWOODS - 1985-88

TRANSPORT AT HIGH AND LOW PRESSURE LEVELS

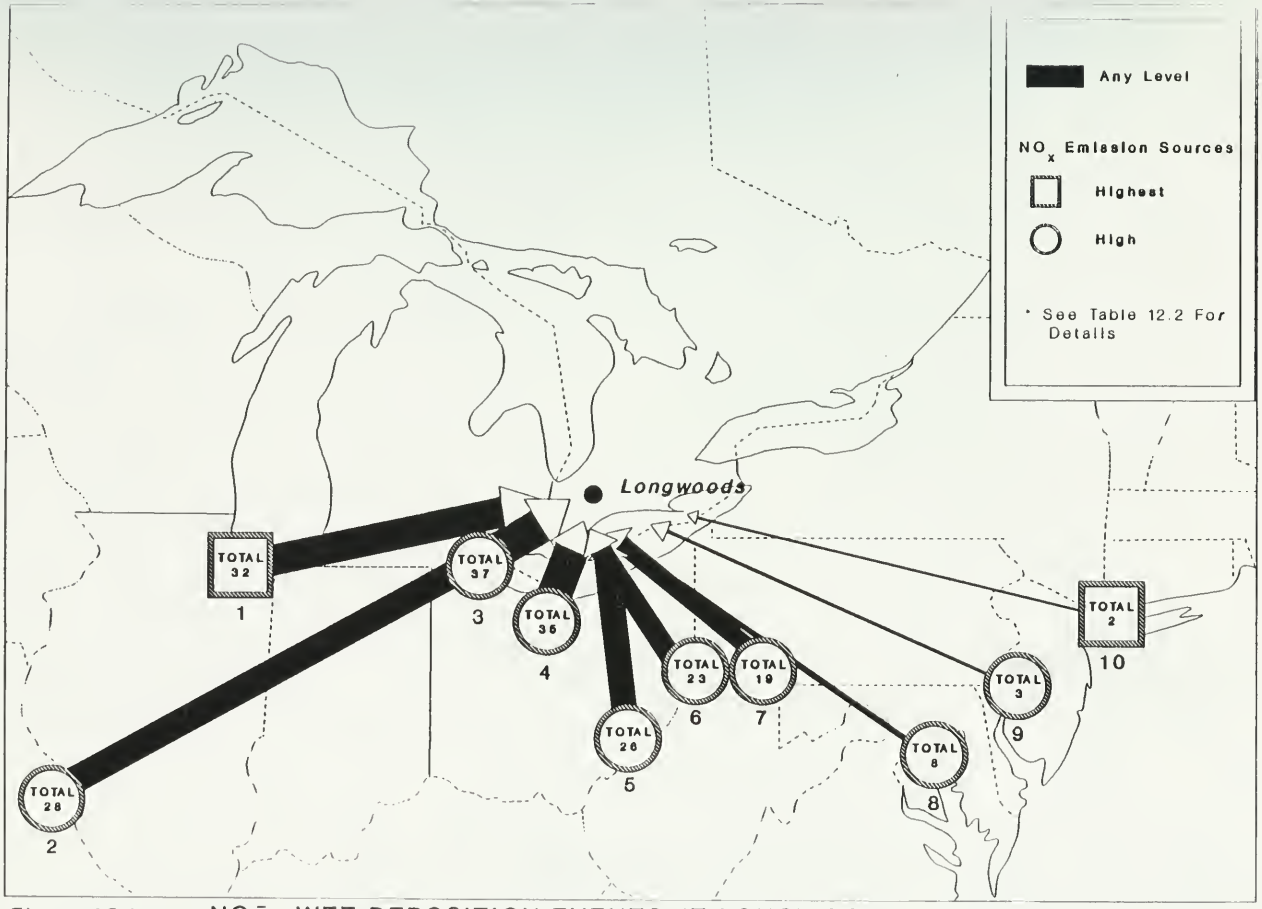


Figure 25.3 NO_3^- WET DEPOSITION EVENTS AT LONGWOODS - 1985-88

TRANSPORT AT ANY PRESSURE LEVEL